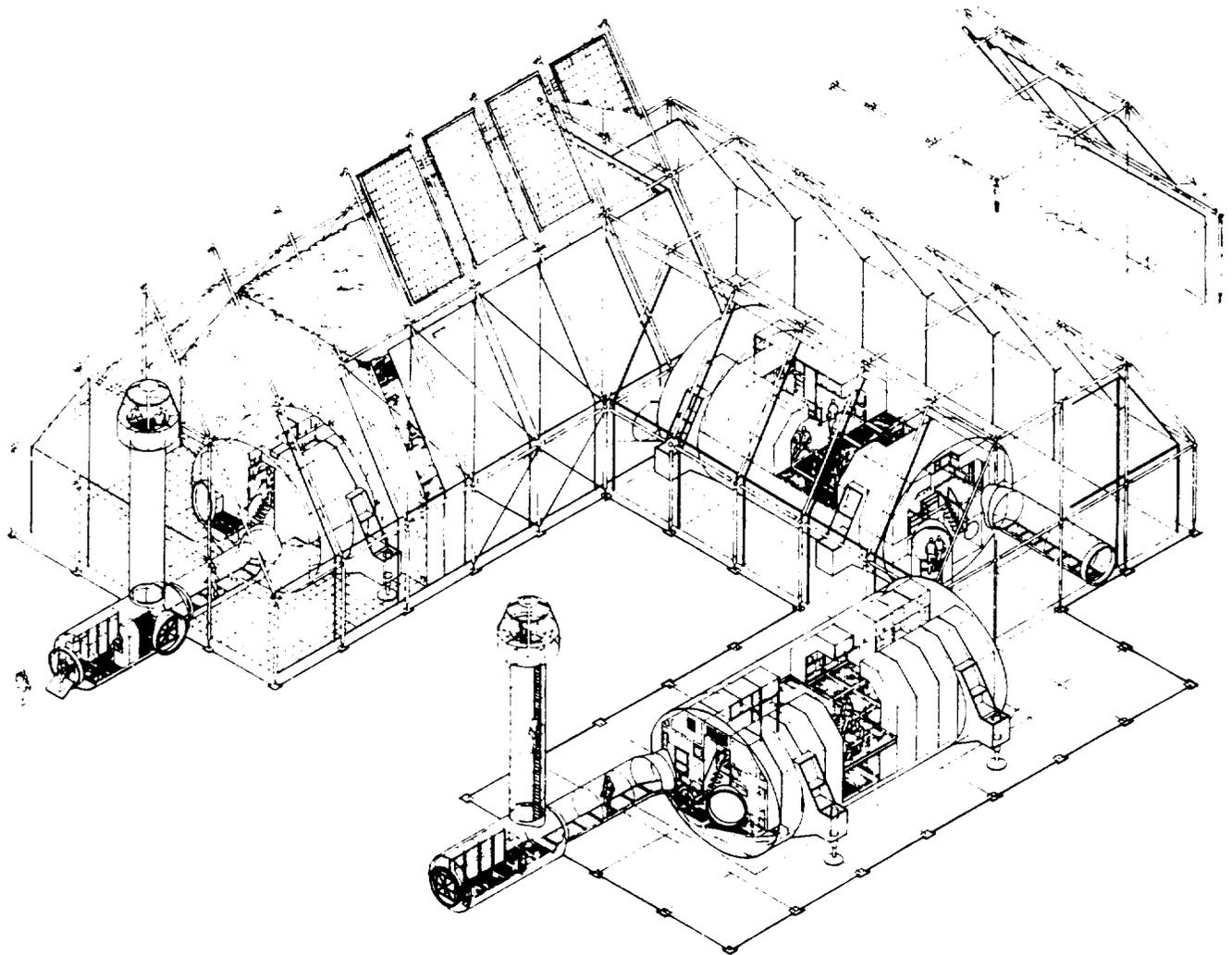


Partial Gravity Habitat Study: with application to Lunar Base Design



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Sasakawa International
Center for Space Architecture

University of Houston
College of Architecture

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**PART I
INTRODUCTION**

1.0 General

1.1 Overview

The purpose of this study was to investigate comprehensive design requirements associated with designing habitats for humans in a partial gravity environment, then apply them to a lunar base design. Other potential sites for application include planetary surfaces such as Mars, variable gravity research facilities, or a rotating spacecraft.

Design requirements for partial gravity environments include locomotion changes in less than normal Earth gravity; facility design issues, such as interior configuration, module diameter and geometry; and volumetric requirements based on the previous as well as psychological issues involved in prolonged isolation.

For application to a Lunar Base, it was necessary to study the exterior architecture and configuration to insure optimum circulation patterns while providing dual egress; radiation protection issues were addressed to provide a safe and healthy environment for the crew; and finally, the overall site was studied to locate all associated facilities in context with the habitat. Mission planning was not the purpose of this study; therefore, a Lockheed scenario was used as an outline for the Lunar Base application, which was then modified to meet the project needs.

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2.0 Goal

2.1 Overview

The goal, or purpose of this report was to formulate facts on human reactions to partial gravity environments, derive design requirements based on these facts and apply the requirements to a partial gravity situation which, for this study, was a lunar base.

3.0 Scope

3.1 Overview

The scope, or range of this study was to investigate architectural and humanistic design criteria in partial gravity environments. Therefore, the decisions and results of this study were based on human safety and comfort for extended stay in isolated space environments. Results have yielded human requirements for partial gravity based on physical and psychological criteria.

4.0 Assumptions

4.1 Assumptions

A Heavy Lift Launch Vehicle (HLLV) must be available that can lift a module size of 22' (6.7 m) by 57.5' (17.2 m) and a weight of approximately 77,000 lbs. (35,000 kg).

A Space Operations Center (SOC) needs to be in operation in LEO to support a planetary base or construct a Mars vehicle, whichever application is chosen.

If a planetary base is the application, such as the Moon, a lander must be available that can land a module weighing 35 metric tons and is 6.7 m by 17.2 m. There must then be the availability of a vehicle that can maneuver the module once on the surface. Without these two vehicles, this concept can not be implemented.

An assumption has also been made that radiation protection for a lunar application is desirable for at least part of the base (Silberberg et al, 1985). The portion of the base that is covered would act as a safe haven for the rest of the base, while the remainder of the base is only thermally shielded.

For a lunar base, a LOX (liquid oxygen) plant will probably be the major function, therefore the mining equipment needed for the plant can be shared to aid the construction process.

PART II PARTIAL GRAVITY DESIGN REQUIREMENTS

Part II of this report will address the issues of how partial gravity affects the design of a human habitation environment. This investigation draws conclusions on various design issues and establishes design requirements for a partial gravity environment.

Part II covers such issues as human locomotion in partial gravity, facility design issues and volumetric requirements.

5.0 Introduction

5.0 Introduction

This study investigates comprehensive design requirements associated with designing habitats for humans in a partial gravity environment. Potential applications include planetary surfaces such as the Moon or Mars, or a rotating vehicle such as a variable gravity research facility or a spacecraft to Mars. Design requirements include human locomotion changes in partial gravity, facility design issues and volumetric requirements based on the previous as well as psychological issues involved in prolonged isolation.

Human locomotion changes are investigated based on experiments performed during the Apollo missions. Results are used to study the impacts on facility design.

Facility design issues, such as functional layout and geometry, are investigated to provide basic architectural requirements for design. Application of these issues are shown further in section 11.0.

Volumes required for crew habitation are derived from a comprehensive study of human needs for extended spaceflight and settlement.

6.0 Locomotion

6.0 Introduction

For design in a partial gravity environment, the issue of human locomotion becomes very important. A partial gravity environment is different from normal Earth gravity (1g) in that human walking and running gaits change, posture changes, and the level of traction changes. The following discusses the differences that are known, and speculates as to how these differences will affect design of a partial gravity habitat.

6.1 Human Walking and Running Gaits

Humans are designed to walk in a normal 1g environment and have adapted to a certain force and traction due to that gravity level. A change in the gravity level changes the forces and traction acting on the human body and, therefore, changes the gait. A comparison of Earth gravity and partial gravity walking and running gaits is shown as follows:

One-G Walking - Muscular energy is expended to lift the legs thus creating potential energy. This lifting of the leg offsets the center of gravity of the body in the forward direction. The result is an acceleration in the forward direction (the transfer of potential energy into kinetic energy). In the case of walking, potential energy and kinetic energy are out of phase (Margaria & Cavagna, 1964). In other words, some of the kinetic energy is turned into potential energy when the body is lifted, thus causing forward motion.

One-G Running - The shift from walking to running takes place at a speed of 8.5 km/hr, at which point the potential energy, accumulated during the body lift, about equals the kinetic energy. Higher speeds require acceleration to be sustained by a direct muscular push, which increases both kinetic and potential energy. The transition from walking to running puts both kinetic and potential energy in phase (Margaria & Cavagna, 1964). In other words, the kinetic

energy and potential energy become equal to sustain the forward speed changes in the step cycle.

Partial-G Walking - In partial gravity (less than one Earth gravity), less muscular energy is expended, thus making less potential energy available. Less acceleration in the forward direction makes walking velocities lower, thus the critical speed at which walking shifts to running becomes lower. In a partial gravity situation, such as the Moon (1/6g), walking is impractical and slow (Margaria & Cavagna, 1964).

Another aspect of walking in partial gravity is the fact that astronauts "bounce" higher because they are used to expending Earth gravity forces to walk. Extended stay in a low gravity environment will probably result in a minimization of this "bouncing" due to muscle atrophy and the astronauts' adjustment to the low gravity environment.

A third aspect of walking in partial gravity is the fact that the body inclination (forward walking angle) is increased. Figure 6.1.1 and 6.1.2 show the differences between body inclinations in Earth gravity and partial gravity.

Partial-G Running - As in walking, the maximum speed for running is lower in a partial gravity situation, because the low apparent weight of the astronaut reduces the vertical force component of traction producing movement (Margaria & Cavagna, 1964). This means the astronauts will have a tendency to slip.

Partial gravity running also has the same aspects regarding "bouncing" and body inclinations. Body inclinations for running can also be seen in figures 6.1.1 and 6.1.2.

Partial-G Jumping - Jumping helps in traction by increasing the vertical force component of the maneuver. Partial gravity locomotion has the advantage of having low energy cost of speed maintenance per distance covered than that required in a 1g environment (Margaria & Cavagna, 1964). Simply stated, humans can jump higher and farther in partial gravity making it easy to cover a large distance,

however, it is more difficult to stop due to reduced traction.

Partial-G Loping - The most natural or comfortable gait utilized in partial gravity simulation studies is a loping gait of about 10 ft./sec. (3 m/sec.), which is much faster than the most comfortable walking gait on Earth of about 4 ft./sec. (1.2 m/sec.) (Hewes et al., 1966). This is due to reduced energy requirements needed to accelerate.

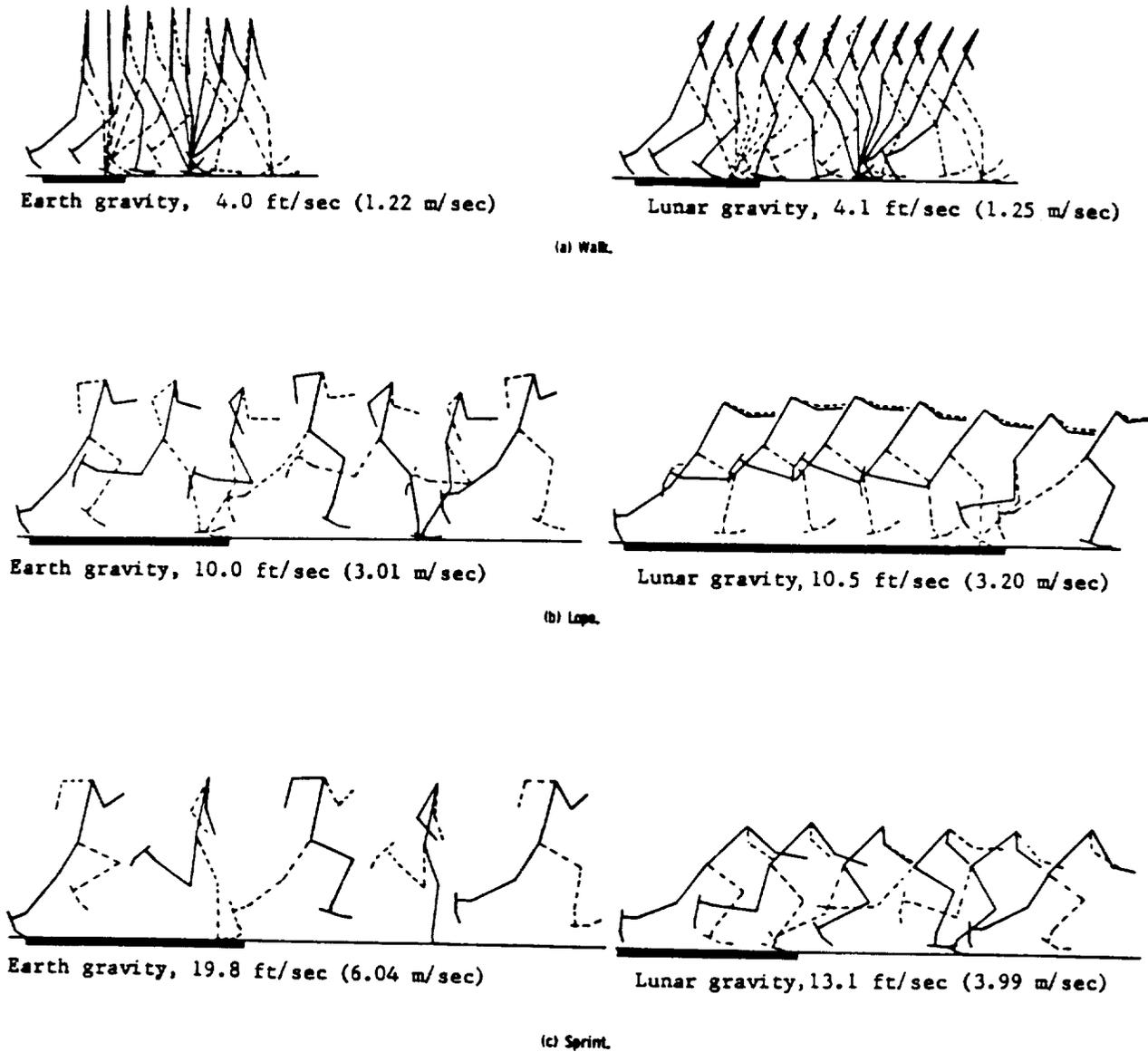


Figure 6.1.1 Body Inclinations (Hewes et al., 1966).

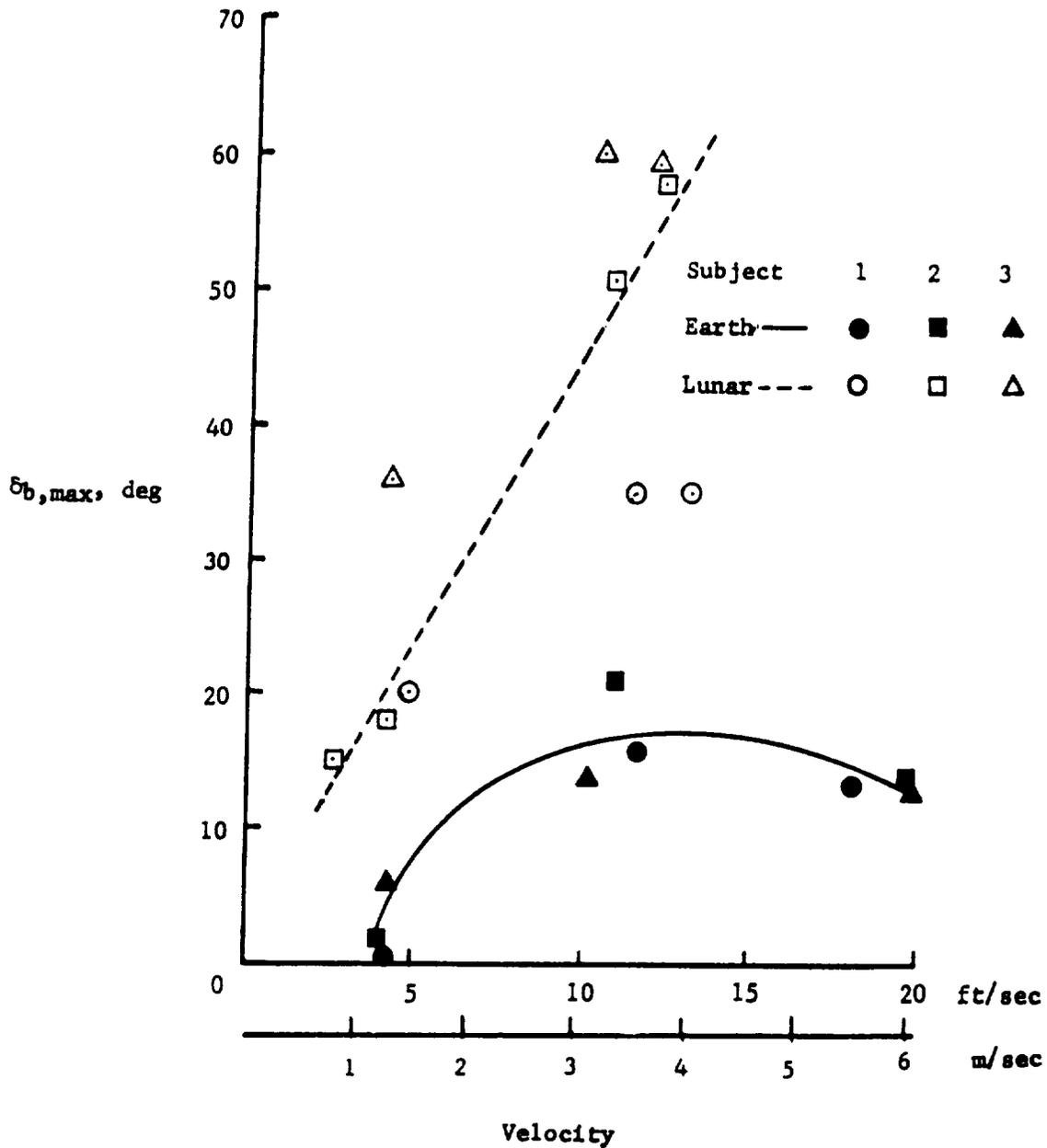


Figure 6.1.2 Body Inclination Against Velocity (Hewes et al., 1966).

6.2 Posture

Human posture in a partial gravity environment differs from posture in a 1g environment. In a partial gravity environment, as the speed is increased, the forward inclination of the body gets progressively larger. For example, the inclination of a sprinting gait on the lunar surface is 60° while the same gait on the Earth is only 10° (Hewes et al., 1966). Figures 6.1.1 and 6.1.2 show, visually, the differences between body inclinations in 1g and 1/6g.

6.3 Traction

The reduction of traction can make human balance and locomotion hazardous in any environment. With a reduction in gravity, a human experiences a reduction in the friction between himself and the surface of the ground. Another constraint affecting locomotion is that the inertial force required to start moving from a complete stop is the same as it is in 1g; therefore, the subject must overcome the same inertial force in partial gravity as in 1g utilizing less traction.

Some of the adverse effects of low traction can be reduced through effective design. Traction effects in partial gravity could be offset by using high-traction floor surfaces, hand/foot mobility aids and increased corridor volume for starting and stopping.

6.4 Conclusions

Human locomotion in partial gravity is quite different than that of a 1g environment. In general, a person would lean forward more, whether walking or running, and adjust to the new environment. This can be offset somewhat by good design.

7.0 Facility Design

7.0 Introduction

Partial gravity habitats are affected by mission parameters as well as the varying gravity level. Mission parameters that affect the design of partial gravity habitats include mission length and activity level as well as architectural issues, such as the functional layout and geometry required to make the habitat function properly.

7.1 Mission Length

Mission length is determined by factors such as destination and planned operations, which affect the design of facilities directly in the form of crew habitat volumes and comfort levels. The requirements of the crew increase as the length of the mission increases (NASA-STD-3000, 1987).

Short Duration Mission - For a short duration mission of a few days to a couple of weeks, crews can share personal quarters by rotating shifts, as they do when the Space Shuttle carries Spacelab. Crew members also do not need near as much volume for recreation, exercise, health maintenance, dining, etc. due to the time factor and the fact that crews can rotate shifts, which reduces redundancy of space.

Medium Duration Mission - For a medium duration mission of less than six months, crews begin to require their own sleeping quarters as well as more extensive personal hygiene areas, etc. The crews will also begin to work on the same shifts as Earth work shifts, which will require more volume for eating and dining facilities as well as a meeting facility that will house the entire crew.

Long Duration Mission - For long duration missions of six months or more, crews begin to require all the necessary "comforts of home". Each crew member will require a private sleeping area with private storage, a dressing area

and a sitting area. Full recreational facilities and exercise facilities will be required as well as a complete health maintenance facility.

7.2 Crew Activity Level

In the past, short duration missions close to the Earth have demanded a maximum amount of time and effort from the crew. This may change as missions move away from the Earth and mission times increase substantially. One example is a trip to Mars, with the travel time estimated in years. The crew would probably take advantage of the space environment to perform experiments, but the activity level is not likely to be nearly as intense as past missions due to mass and volume considerations.

A change in activity level would also have an effect on the crew design requirements. A high activity level could demand shift work, resulting in more shared facilities and less volume. A low level of activity could demand more volume for leisure activities.

7.3 Functional Layout

The most logical way to subdivide a habitable volume is on the basis of function. Due to their nature, various functions dictate adjacency or separation from each other. The connections between these functions must accommodate each function's specific constraints. Four functional units can be derived from typical crew activities during a mission:

- Private Unit (Personal Quarters)
- Public Unit (Dining, Recreation and Exercise)
- Work Unit (Mission Operations and Management)
- Living Unit (Habitation)

A diagram of these breakdowns can be seen in figure 7.3.1. The separation and adjacencies of these four functions is based on factors such as noise, mechanical issues and privacy. Separation could either be psychological (visual separation) or physical (wall or door). Optimal design

should have separations between functions that have different noise, lighting, vibration or privacy requirements.

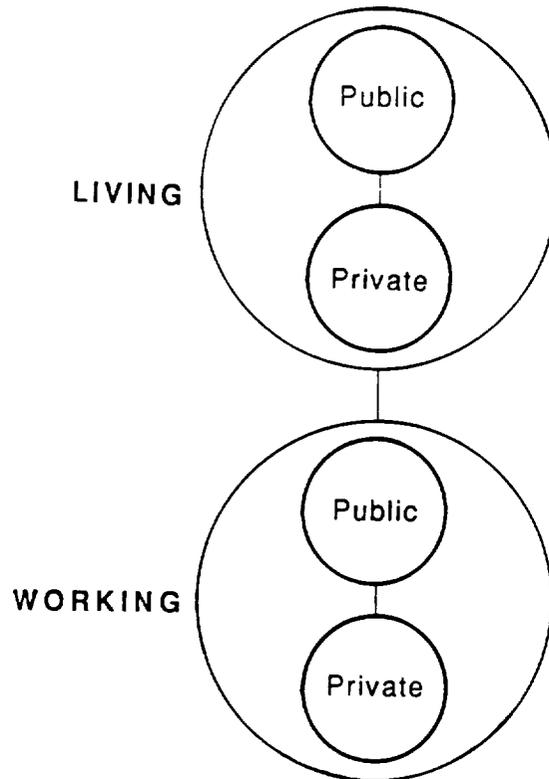


Figure 7.3.1 Concept Diagram for Functional Layout

7.4 Geometry

Inherent in the design of space hardware is the fact that all habitable spaces must occur within pressure hulls. Another given fact is that the most efficient geometry for a pressure hull is the circular section. Although structurally efficient, the circle is not efficiently fitted to the linear design of the human figure, which traditionally has orthogonal patterns for design. However, the circular section is a geometry that we must use, for efficiency reasons, in the design of habitable spaces.

The two configuration options considered for the *Space Station Freedom* were the vertical, with the long axis of the module parallel to the long axis of the body, and the horizontal, with the long axis perpendicular to the long axis of the body (Figure 7.4.1). In microgravity, these two configurations present a closer trade study than in a partial

gravity environment. In partial gravity, height, egress and vertical circulation problems inherent to the vertical configuration make it impractical. We, therefore, chose to look at horizontal configurations.

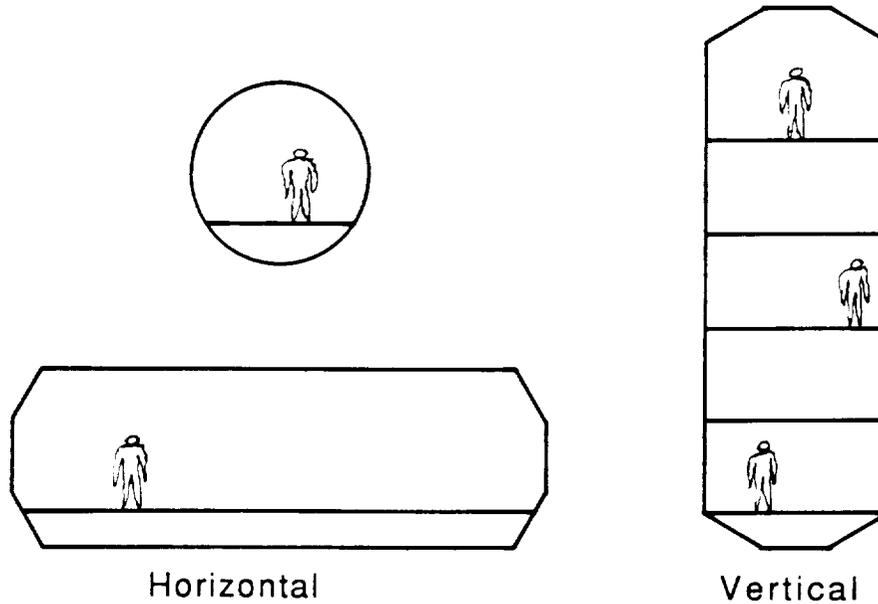


Figure 7.4.1 Configuration Options

The next trade to be studied lies between having a one (one "story" or floor) or two level (two "story" or floors) interior configuration (Figure 7.4.2). Considerations in this trade are the overall module size being considered (which is determined by transportation and handling requirements), and the internal circulation requirements (corridor, ladders, etc.).

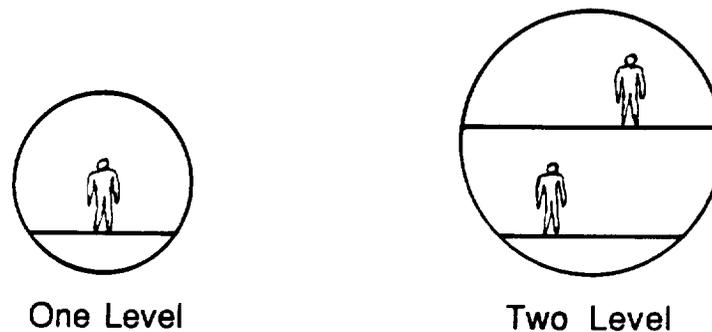


Figure 7.4.2 Interior Configuration Options

From an internal architecture standpoint, the two level module configuration is more efficient for long duration missions because the equipment to circulation ratio is minimized. The two level module is more space efficient than a one level configuration. It also affords the possibility of creating higher, two level spaces as required. An analysis of the two-level configurations is shown in section 11.1.

Another aspect of geometry is the need for a partial gravity habitat to be reconfigurable as well as expandable. Internal structure must be designed so that, if the need arises to reconfigure the internal layout, the task can be accomplished without great effort. The modules should also be standardized so that expansion is just a matter of bringing in another module and attaching it to the existing configuration. External geometry studies are discussed in section 12.1.

8.0 Volume Study

8.0 Introduction

The following study investigates volumes required for human habitation in a partial gravity environment. The volumes calculated are space efficient yet psychologically acceptable for long duration isolation. These volumes are applicable to a partial gravity environment for places such as a lunar base, martian base, or an artificial gravity space habitat. The volumes calculated and recommended for long duration space settlement are a galley, dining/wardroom area, recreation hall, exercise area, health maintenance facility, personal quarters, personal hygiene/waste management facilities, laundry, EVA storage, laboratory/work space, maintenance, circulation, ECLSS and safe haven.

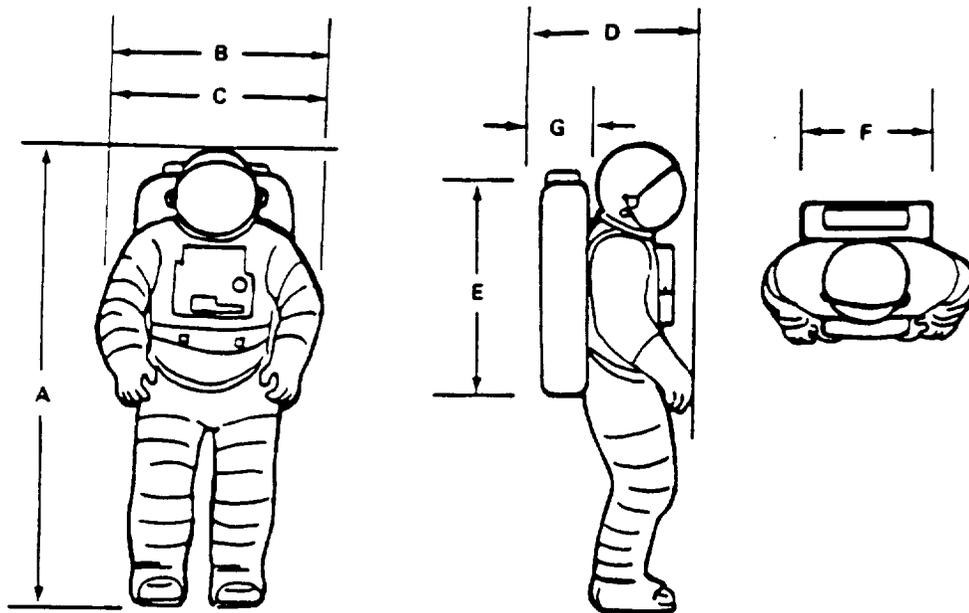
Partial gravity volume requirements differ from the *Space Station Freedom* in that there is a certain level of gravity which restricts the use of space due to inherent needs and the reach envelope in a gravity environment. In other words, crew members cannot use the area in the ceiling and floors and cannot sleep on the walls and ceiling in partial gravity as they can in microgravity. However, similarities are that the equipment sizes and design (in a "rack" system) will be basically the same. Therefore, the following study investigates volumes for a partial gravity habitat, using the *Space Station Freedom* equipment and "rack" system as a standard, and adapting it to a partial gravity situation.

8.1 Anthropometric Data

The anthropometric data presented here was used to determine the standard dimensions for widths of corridors, usable heights of spaces and racks, and standard ceiling heights. These standards are based on safety, usable dimensions derived from anthropometric data and the psychological feeling of space.

Circulation paths need to be wide enough for two astronauts to pass each other safely while outfitted in a spacesuit.

This is a safety precaution in case of depressurization of the module. Dimensions of an astronaut in a spacesuit are shown in figure 8.1.1. Because the D dimension is 27"(69cm) and the B dimension is 33.4"(85cm), the standard clear space of a circulation path will range from 54"(1.37m) to 67"(1.7m). To avoid excess space that will only be useful in an emergency situation, 54"(1.37m) will be used as the standard width for circulation paths (two astronauts facing each other while outfitted in a spacesuit) (NASA-STD-3000, 1987).



	Size range	
	5th Percentile Female	95th Percentile Male
A - Height	171.5 cm (67.5 in)	191.8 cm (75.5 in)
B - Maximum breadth at elbows (arms relaxed)	-	84.8 cm (33.4 in)
C - Maximum breadth at elbows (arms at side)	-	66.0 cm (26.0 in)
D - Maximum depth with PLSS/SOP	66.0 cm (26.0 in)	68.6 cm (27.0 in)
E - PLSS height	81.3 cm (32.0 in)	
F - PLSS breadth	58.4 cm (23.0 in)	
G - PLSS depth	17.8 cm (7.0 in)	

PLSS - Primary life support system
SOP - Secondary oxygen pack

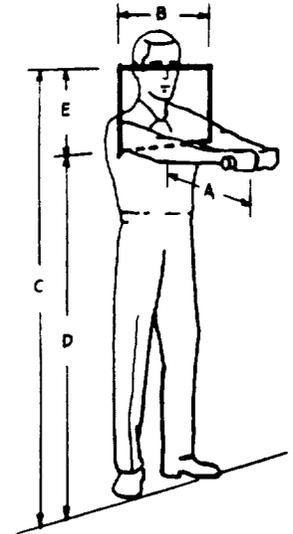
Figure 8.1.1 Space Suit Dimensions (NASA-STD-3000, 1987).

Usable reach envelopes for humans are shown in figure 8.1.2. The reach depth ranges from 24.5"(62cm) to 26.75"(68cm), while reach height ranges from 84.7"(2.15m) for women to 90.8"(2.31m) for men (Woodson, 1981).

Standing, Forward Reach (Both Arms)

	Percentiles				
	5th	25th	50th	75th	95th
A. Depth of reach Range: 17.50 to 25.25 SD: 1.50	19.25 in	21.00 in	22.25 in	22.75 in	24.50 in
B. Breadth of aperture Range: 15.00 to 20.25 Mean: 17.69 SD: 1.19	15.50 in	17.00 in	17.75 in	18.50 in	19.50 in
C. Floor to top of aperture Range: 58.75 to 70.50 SD: 2.34	61.00 in	63.50 in	65.25 in	66.50 in	69.00 in
D. Floor to bottom of aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25 in	54.75 in	56.00 in	57.25 in	59.00 in
E. Vertical dimension of aperture	(1)	(1)	(1)	(1)	(1)

(1) 16.75 in.



Standing, Forward Reach (Preferred Arm)

	Percentiles				
	5th	25th	50th	75th	95th
A. Depth of reach Range: 19.50 to 27.50 Mean: 23.61 SD: 1.82	20.25 in	22.25 in	23.75 in	25.00 in	26.75 in
B. Breadth of aperture: 12.00					
C. Floor to top of aperture Range: 58.25 to 70.50 Mean: 64.88 SD: 2.36	61.00 in	63.25 in	65.00 in	66.25 in	69.00 in
D. Floor to bottom of aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25 in	54.75 in	56.00 in	57.25 in	59.00 in
E. Vertical dimension of aperture	(1)	(1)	(1)	(1)	(1)

(1) 16.75 in.

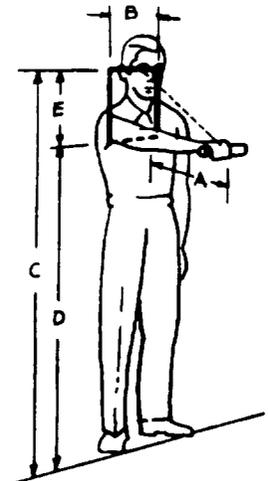
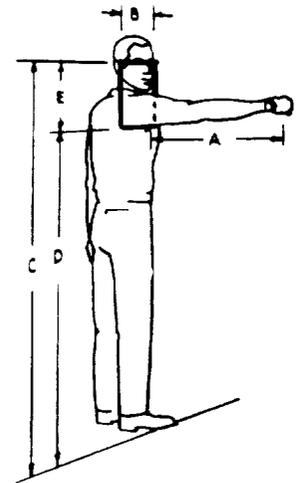


Figure 8.1.2 Anthropometric Data (Woodson, 1981).

Standing, Lateral Reach (Preferred Arm)

	Percentiles				
	5th	25th	50th	75th	95th
A. Depth of reach Range: 21.75 to 28.63 Mean: 24.65 SD: 1.51	22.00 in	23.50 in	24.75 in	25.75 in	26.75 in
B. Breadth of aperture 10.00					
C. Floor to top of aperture Range: 58.25 to 70.00 Mean: 64.70 SD: 2.32	60.75 in	63.25 in	64.25 in	66.00 in	68.75 in
D. Floor to bottom of aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25 in	54.75 in	56.00 in	57.25 in	59.00 in
E. Vertical dimension of aperture	(1)	(1)	(1)	(1)	(1)

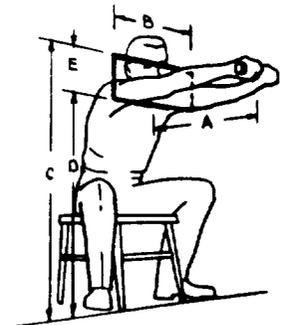
(1) 16.5 in.



Seated, Forward Reach (Both Arms)

	Percentiles				
	5th	25th	50th	75th	95th
A. Depth of reach Range: 14.00 to 23.50 Mean: 18.26 SD: 2.15	15.00 in	16.50 in	17.75 in	19.50 in	22.25 in
B. Breadth of aperture Range: 13.50 to 18.75 Mean: 16.12 SD: 1.25	13.75 in	15.25 in	16.00 in	17.00 in	18.25 in
C. Floor to top of aperture Range: 39.25 to 51.00 Mean: 43.25 SD: 2.05	19.75 in	41.75 in	43.00 in	44.25 in	46.50 in
D. Floor to bottom of aperture Range: 32.50 to 41.75 Mean: 36.59 SD: 1.59	34.25 in	35.50 in	36.50 in	37.50 in	39.00 in
E. Vertical dimension of aperture	(1)	(1)	(1)	(1)	(1)

(1) 12.25 in.



Selected Working-Position Data for U.S. Army Men and Women (Wearing Typical Army Clothing)¹⁸

Anthropometric Data for U.S. Male and Female Personnel: Common Working Positions. Percentile Values

	5th Percentile		95th Percentile	
	Men	Women	Men	Women
A. Overhead reach	78.9 in	73.0 in	90.8 in	84.7 in
B. Overhead reach, breadth	13.9 in	12.4 in	16.5 in	14.9 in
C. Bent torso height	49.4 in	44.4 in	59.0 in	54.6 in
D. Bent torso breadth	16.1 in	14.5 in	19.0 in	17.1 in
E. Kneeling height	48.0 in	45.1 in	53.9 in	51.3 in
F. Kneeling leg length	25.2 in	23.3 in	29.7 in	27.8 in
G. Overhead reach, sitting	50.3 in	46.2 in	57.9 in	54.9 in
H. Functional leg length	43.5 in	39.2 in	50.3 in	46.7 in
I. Bent knee height, supine	17.6 in	16.3 in	21.1 in	19.5 in
J. Horizontal length, knee bent	59.4 in	55.2 in	68.1 in	64.5 in
K. Functional reach	33.2 in	28.9 in	39.8 in	36.5 in

Source: MIL-STD-1472B, Notice—2, May 10, 1978.

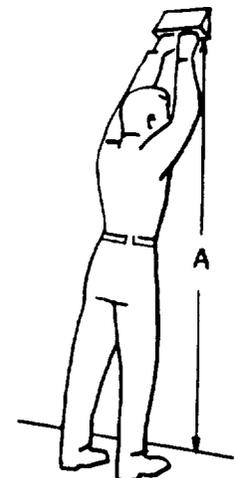


Figure 8.1.2 (Continued).

Racks should be sized according to the anthropometric data presented in figure 8.1.2. Therefore, usable rack space is approximately 24"(61cm) in depth by 84"(2.13m) in height. Standard *Space Station Freedom* racks are approximately 40"(1m) in depth, to allow for wiring of equipment, etc., and 84"(2.13m) in height. Therefore, standard rack sizes will be 40"(1m) deep by 42"(1.06m) wide by 84"(2.13m) high for this study (NASA-JSC Crew Systems Review, 1988).

Ceiling height standards are based on psychological feelings of height as well as usable height. Because of the remoteness of a space habitat, the psychological feeling of space is very important. As shown in figure 8.1.2, usable height for the average human is around 7'-0" (2.13 m). On Earth, in the United States in particular, the standard ceiling height is 8'-0"(2.44m). The extra height is needed for psychological needs of humans.

It has been suggested by some that a ceiling height of 10'-0"(3.05m) might be used for a lunar base because, when humans walk in a 1/6 gravity environment, they bounce higher due to reduced gravity. I contend that this is not necessary or practical because (1) humans have a stooped posture due to reduced gravity levels (Hewes, Spady, and Harris, 1966) and (2) the "extra" 3'-0" above the average human's reach height is unusable, therefore wasteful, and a very costly luxury.

Figure 6.1.1 graphically shows the differences in human body inclinations between the Earth and the Moon at various velocities. Figure 6.1.2 is a graph showing the exact body inclination differences between the Earth and the Moon at various velocities. These inclinations allow the body more headroom in a partial gravity environment due to the angle of the body.

It is probable that humans will eventually begin to adapt walking skills in a partial gravity environment over time, particularly after extended exposure, when muscles will begin to atrophy. Therefore, a ceiling height of 8'-0" is used for the remainder of this study.

8.2 Galley

The galley must provide capabilities for preservation, preparation, storage, dispensing and disposal of food and wastes (NASA-STD-3000). Aside from the special fluid handling problems in microgravity, human equipment needs are not affected by the presence of gravity, so *Space Station Freedom* standards may be applied. The galley elements should include (NASA-JSC Crew Systems Review, 1988):

1. Ambient Storage
2. Refrigerator/Freezer Storage
3. Bulk Food and Beverage Storage/Dispensing
4. Automation and Food Inventory Control
5. Microwave/Convection Oven
6. Deployable Counter (Food Preparation)
7. Trash Compactor and Storage
8. Dishwasher/Dryer
9. Handwasher/Dryer
10. Water Dispenser

The galley should provide space for 14-day supply of food and beverages (NASA-JSC Crew Systems Review, 1988). The volume varies depending on the number of crew. The backup food and trash storage will be stored in a logistics module and transferred to the galley every 14 days. This volume also depends on the number of crew and the re-supply cycle.

The following list (table 8.2.1) shows some estimated volumes for the *Space Station Freedom* galley.

Actual design of the galley will incorporate the above volumes into a "rack" system for ease of assembly and maintenance. Standard racks for this study are dimensioned previously as 40"(1m) deep by 42"(1.06m) wide by 84"(2.13m) high, having a volume of 82ft.³(2.31m³).

The drawings which follow in figures 8.2.1 and 8.2.2 show a possible layout for the *Space Station Freedom* galley using four (4) racks. This design can accommodate eight (8) crew members and can be applied to a partial gravity design, with consideration for equipment access.

Table 8.2.1 Galley Volumes

Item	Volume (cu. ft./cu. m.)
Daily Food, Frozen (person/day)	0.36/0.010**
Daily Food, Refrigerated (person/day)	0.12/0.003**
Daily Food, Ambient (person/day)	0.20/0.006**
Total	0.68/0.019
Stove	6.00/0.170**
Oven	6.00/0.170**
Dishwasher	12.00/0.340**
Trash Compactor	2.00/0.060**
Utensil/Appliance Storage	7.50/0.210**
Rehydration Ports (2 sets)	1.50/0.040**
Water Heater (20 gallon)	4.00/0.110**
Water Chiller (10 gallon)	2.00/0.060**
Trash Storage (person/day)	0.10/0.003**

** Lewis, 1983

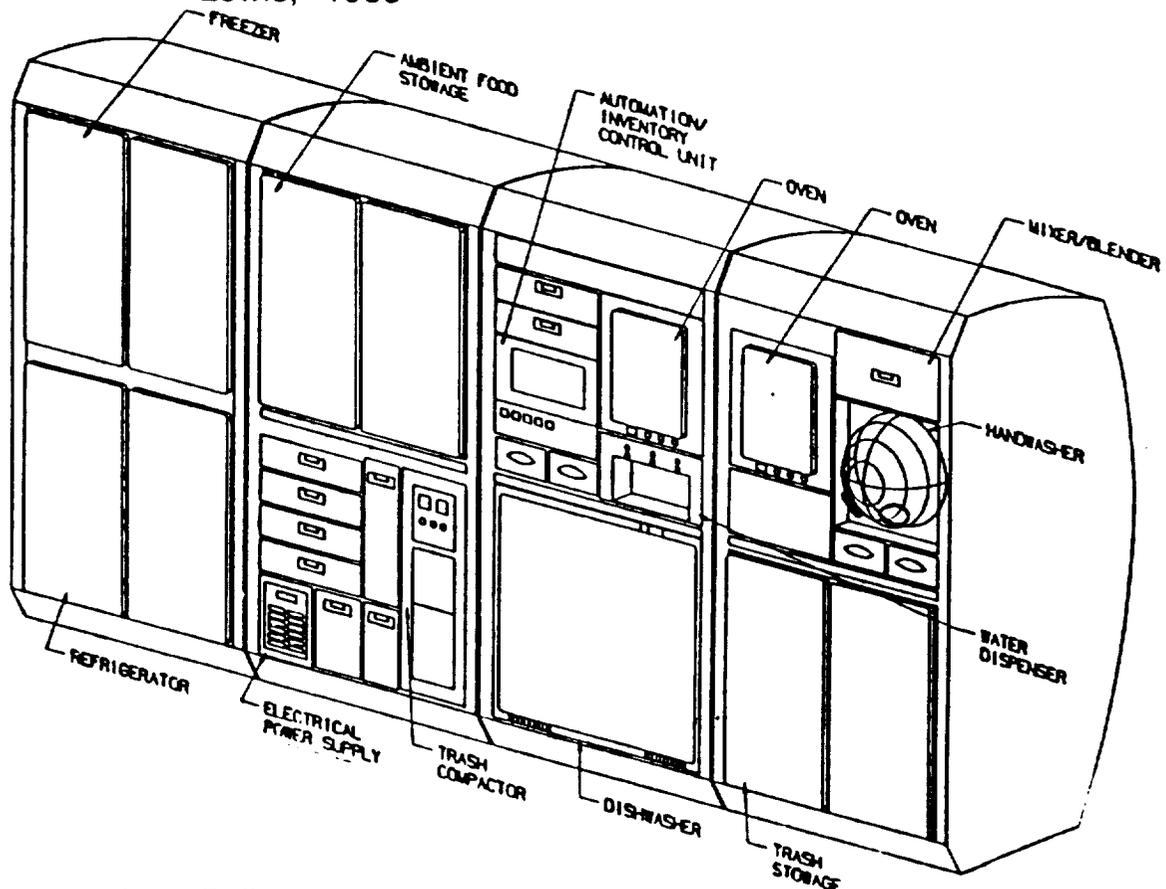
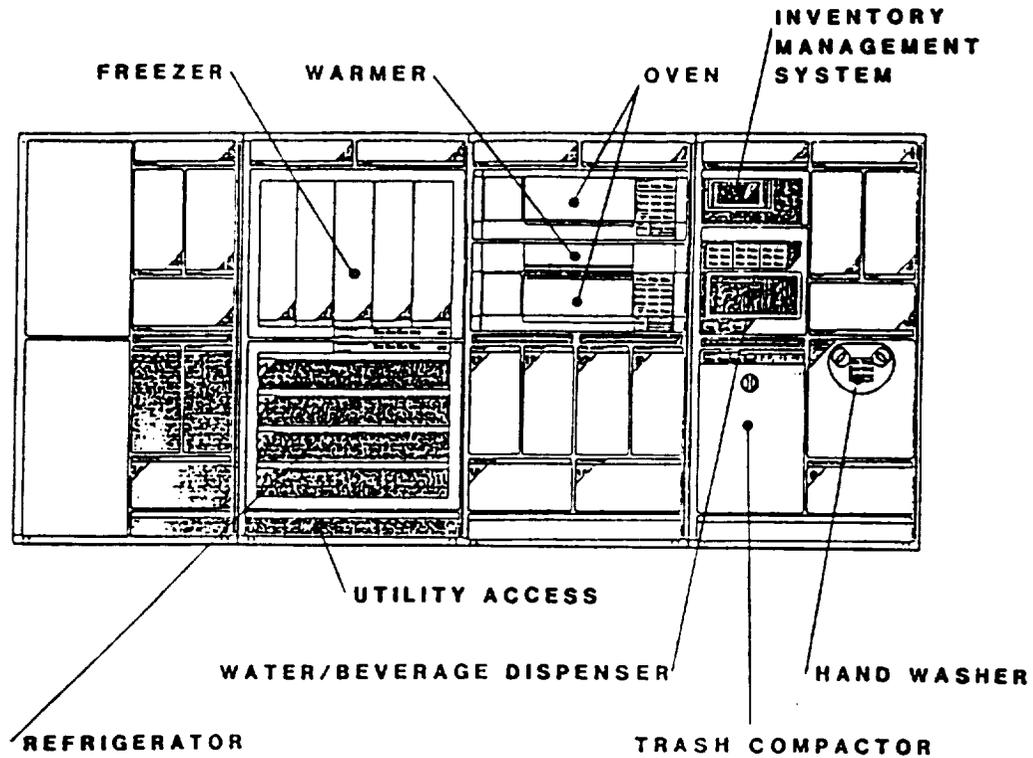


Figure 8.2.1 Galley Layout (NASA-JSC Crew Systems Review, 1988).



NOTE: REMAINING BINS ALLOCATED TO AMBIENT STOWAGE

Figure 8.2.2 Galley Configuration (NASA-JSC Crew Systems Review, 1988).

A more efficient layout of the four rack system for a crew of eight (8) is shown in figure 8.2.3. This layout minimizes the circulation and access space by locating two (2) of the four (4) racks on the opposite side of the aisle. This arrangement also begins to define the galley as a "room", or as its own entity, rather than four (4) racks located on the side of a "hallway".

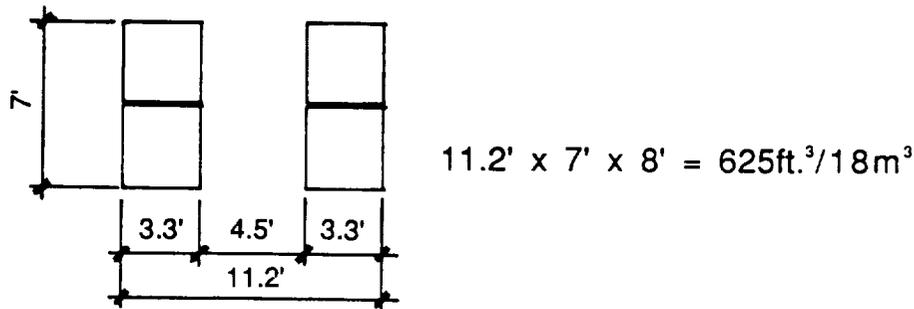


Figure 8.2.3 Suggested Galley Layout.

To accommodate an additional crew of eight (8), the galley would have to be expanded by two (2) racks to accommodate more food storage (freezer, refrigerator, ambient) and trash storage. More volume for additional appliances, etc. can be eliminated by rotation of eating schedules for up to sixteen (16) crew members. The additional food and trash storage would require two (2) more racks, because the crew is doubling in size. A suggested layout for the galley with six (6) racks to accommodate sixteen (16) crew members is shown below in figure 8.2.4.

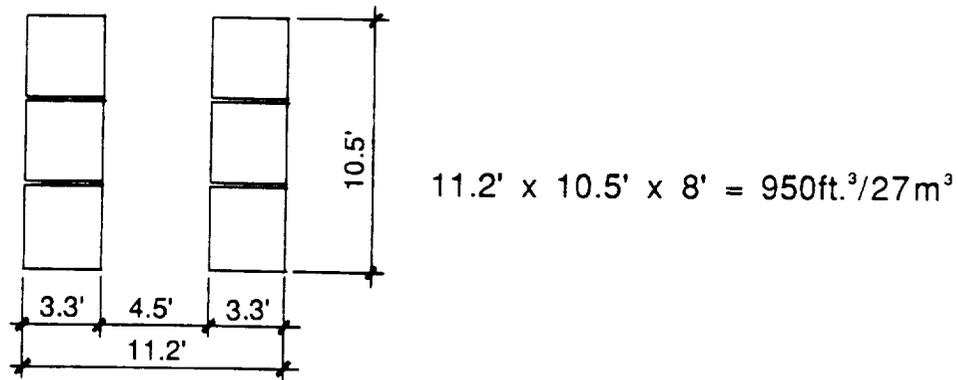


Figure 8.2.4 Suggested Galley Layout.

The volumes required for a galley are summarized in table 8.2.2.

Table 8.2.2 Total Galley Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 8	625/18
9-16	950/27

The contingency food and trash storage depends on the number of crew and the resupply cycle. This volume can be calculated by the following formula:

$$(\text{Food Storage/person/day} + \text{Trash Storage/person/day}) \times \# \text{ of Crew} \times \text{Resupply Cycle}$$

or

$$(0.68\text{ft.}^3/\text{person}/\text{day} + 0.1\text{ft.}^3/\text{person}/\text{day}) \times \# \text{ of Crew} \times \text{Resupply Cycle}$$

Table 8.2.3 shows the results of this formula using a 90-day resupply cycle.

Table 8.2.3 Contingency Food & Trash Storage

# of Crew	Volume (cu. ft./cu. m.)
1 - 4	280/ 8
5 - 8	560/ 16
9 - 12	840/ 24
13 - 16	1125/ 32

8.3 Dining/Wardroom

The dining area should provide adequate seating for the entire crew, so the crew can not only dine at the table but hold meetings and play games, etc. Figure 8.3.1 shows standard dimensions required to give adequate seating space.

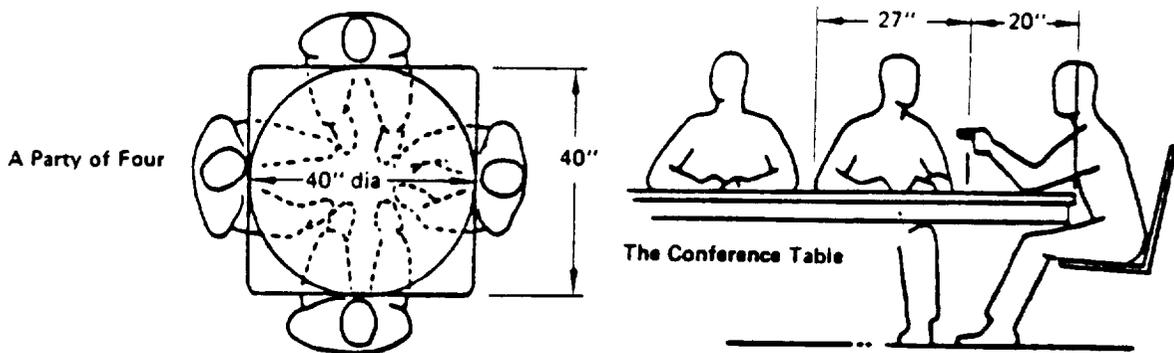


Figure 8.3.1 Table Dimensions (NASA-STD-3000,1987).

The following drawings in figure 8.3.2 show the previous dimension standards incorporated into table layouts for four (4), eight (8), twelve (12) and sixteen (16) people. These layouts assume a 2'-6"(0.76m) seating and circulation area beyond the table.

Table 8.3.1 shows the breakdown of each of the table layouts in volumes. These volumes can be calculated by the following equation:

$$[\text{Table length} + (2 \times 2.5')] \times [\text{Table width} + (2 \times 2.5')] \times 8.0'$$

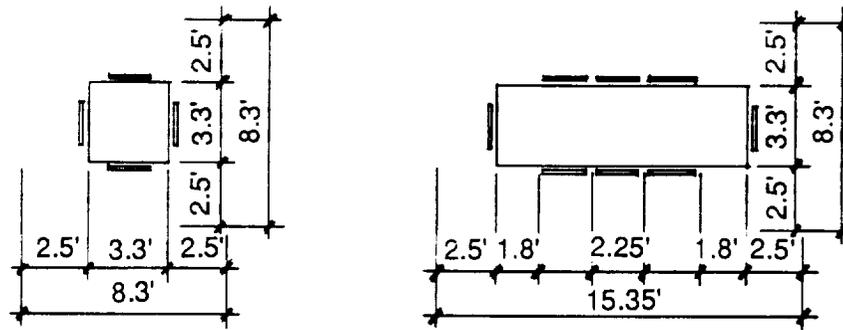


Figure 8.3.2 Table Layouts.

Single tables for twelve (12) and sixteen (16) people become impractical because they are so large and wasteful. Therefore, space for twelve (12) can be made by using one of each of the figure 8.3.2 tables and space for sixteen (16) can be made by using two of the large tables in figure 8.3.2.

Table 8.3.1 Dining/Wardroom Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 4	550/16
5 - 8	1050/30
9 - 12	1600/46
13 - 16	2100/60

8.4 Recreation

The recreation area size and configuration will depend on the type of recreation scheduled. Some of the activities used in antarctic missions and past space missions are reading, conversation, observation, visual entertainment, games and music listening (NASA-STD-3000, 1987). The reading area will probably be included in the personal quarters for privacy, and games will probably be played at the dining table to avoid duplicating space unnecessarily.

Conversation and music listening could be combined in a casual, lounge seating area or, if space is very scarce and valuable, into the dining/wardroom area. In this study, the conversation and music listening is calculated as a separate entity.

Figure 8.4.1 below shows a possible arrangement for a casual lounge, seating area for conversation and possibly music listening. Ninety degrees (90°) is the preferable angle for casual conversation, hence the reasoning for the right angle arrangement.

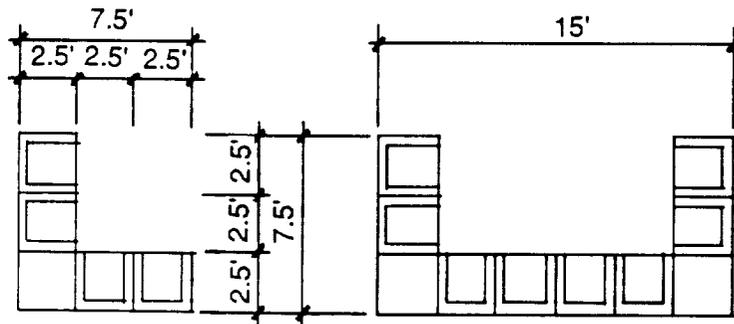


Figure 8.4.1 Seating Arrangement.

Table 8.4.1 shows the volume calculation for the conversation/music listening area based on the above dimensions.

Table 8.4.1 Conversation/Music Listening Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 4	450 / 13
5 - 8	900 / 25
9 - 12	1350 / 38
13 - 16	1800 / 51

The observation area should provide space for viewing from windows. There should be at least one viewport for each eight (8) crew members in the recreation area as well as the exercise area if we assume the *Space Station Freedom* as an analog. The purpose of these viewports is for crew morale. Viewports for scientific observation and EVA viewing should be incorporated into the laboratory/workspace to separate the work-recreation activities. Each viewport should accommodate at least two (2) crew members (Bell & Trotti, 1985) as shown in figure 8.4.2.

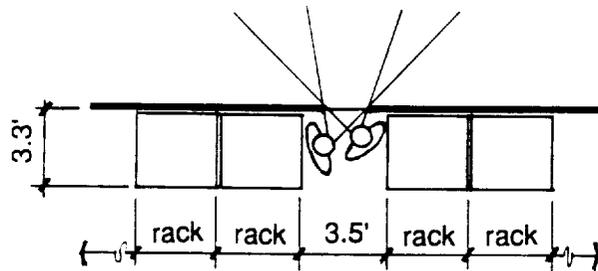


Figure 8.4.2 Viewport Layout.

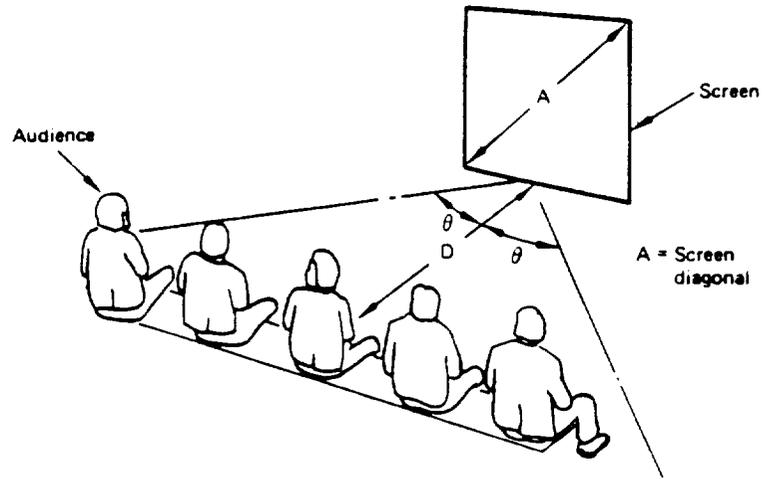
Table 8.4.2 shows the volume calculations for a viewport based on the previous dimensions.

Table 8.4.2 Viewport Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 8	100/ 3
9 - 12	200/ 6

Visual entertainment (movies, tapes, etc.) consists of a seating area, screen and a projection/storage area (NASA-STD-3000, 1987). Figure 8.4.3 shows a formula for calculating the size of a viewing area. Visual entertainment could be incorporated into the dining/wardroom or the casual seating area but, for longer missions, it is desirable to have separate accommodations.

Figure 8.4.4 shows how a seating area might be calculated for a crew of four (4), eight (8), twelve (12) and sixteen (16).



Factor	Optimum	Preferred limits	Acceptable limits
D Viewing distance to the screen	4 x A	3 x A to 6 x A	2 x A to 8 x A
θ Angle off centerline	0 deg	20 deg	30 deg

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Figure 8.4.3 Viewing Area (NASA-STD-3000, 1987).

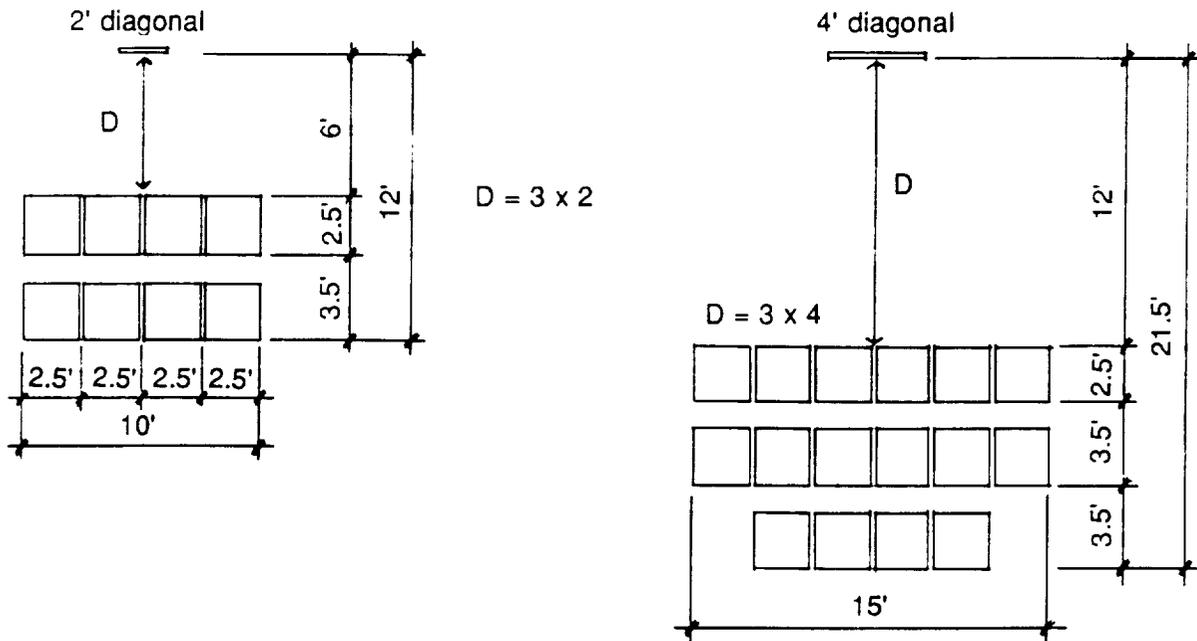


Figure 8.4.4 Viewing Area Layout.

Table 8.4.3 below gives a summary of the volume calculations for a viewing area.

Table 8.4.3 Viewing Area Volumes

<u># of Crew</u>	<u>Volumes(cu. ft./cu. m.)</u>
1 - 4	680/19
5 - 8	960/27
9 - 12	2160/61
13 - 16	2580/73

Table 8.4.4 below summarizes the volumes for a recreation area and gives a total volume for the crew sizes listed. Each volume was given a 10% contingency for equipment storage.

Table 8.4.4 Recreation Area Volumes

<u># of Crew</u>	<u>Volume(cu. ft./cu. m.)</u>
1 - 4	1350/38
5 - 8	2160/61
9 - 12	4080/115
13 - 16	5030/143

8.5 Exercise

Exercise to maintain health in a partial gravity habitat may not be quite as critical or require as much time as in a microgravity environment. However, exercise is still important not only to keep the crew healthy, but to keep them physically active and to allow social interaction. Exercise can make one feel better about oneself and, therefore, promote better and more productive work.

Exercise equipment should be provided to keep the crew in shape for the return from, for example, the 1/6 gravity of the Moon to the 1 gravity level of the Earth. Countermeasure exercises should provide for bone mineral loss, muscular strength loss, and cardiovascular function loss (NASA-STD-3000, 1987). Items may include a treadmill, simulated 1g weight training and a cycle

respectively. A viewport should also be provided to allow visual and psychological relaxation during exercise breaks. Figure 8.5.1 shows a possible layout for an exercise area to accommodate either eight (8) or sixteen (16) crewmembers. Crew of up to sixteen (16) can use the facility on rotated shifts to avoid having to provide duplicate facilities.

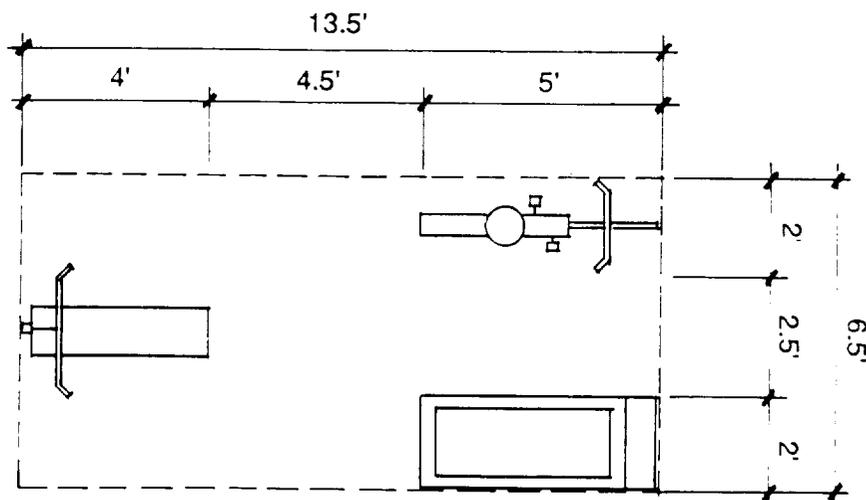


Figure 8.5.1 Exercise Area Layout.

The 4.5' clear space in the middle of the exercise area is consistent with the clear space needed in an emergency situation. If the exercise area is split by the major circulation path of the module, the 4.5' clear space is needed. However, if the exercise area is not split by the major circulation path but is isolated, then the 4.5' could be reduced to 3.0'.

An exercise area for up to sixteen crew members would take up a volume of approximately 700ft.³(20m³).

8.6 Health Maintenance Facility (HMF)

The Health Maintenance Facility (HMF) for the *Space Station Freedom* has been estimated at 320ft.³(9m³) in equipment and work space (Degioanni, 1986). This volume is equivalent to four (4) single racks (2 *S. S. Freedom* racks) of equipment, Spacelab style. Figure 8.6.1 shows a schematic of this facility. Figure 8.6.2 shows a schematic for the *S. S. Freedom* HMF using three (3) standard, full size racks.

The HMF for a lunar base or a Mars spacecraft or base is envisioned as being a larger facility in order to provide more supplies as well as increased capabilities because of the projected length of potential missions and unavailability of near term help.

The HMF for a Lunar or Mars base has been estimated to be approximately 480ft.³(14m³) (Degioanni, 1986). Equipment will probably be housed in three (3) standard *Space Station Freedom* racks in much the same manner as shown in figure 8.6.2. Specific requirements can be found in the NASA Man-Systems Integration Standards (NASA-STD-3000, 1987) in section 10.9.

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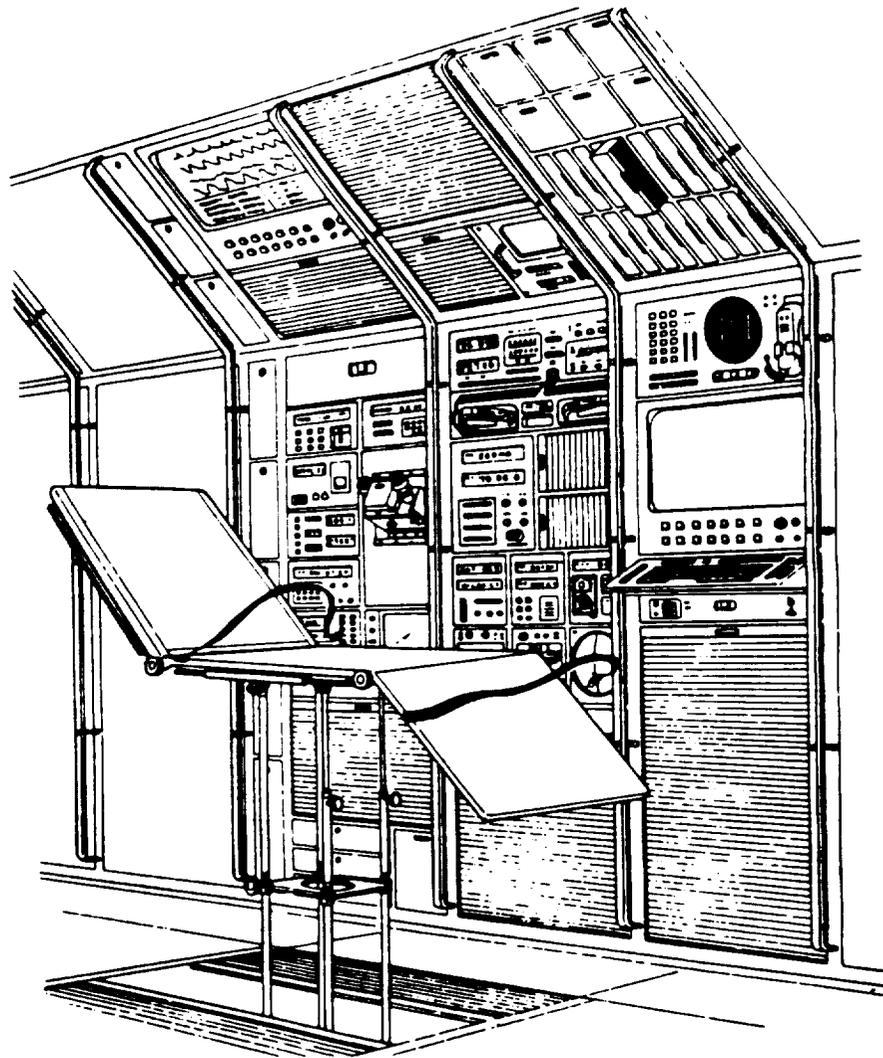


Figure 8.6.1 HMF for *S. S. Freedom* (Degioanni, 1986).

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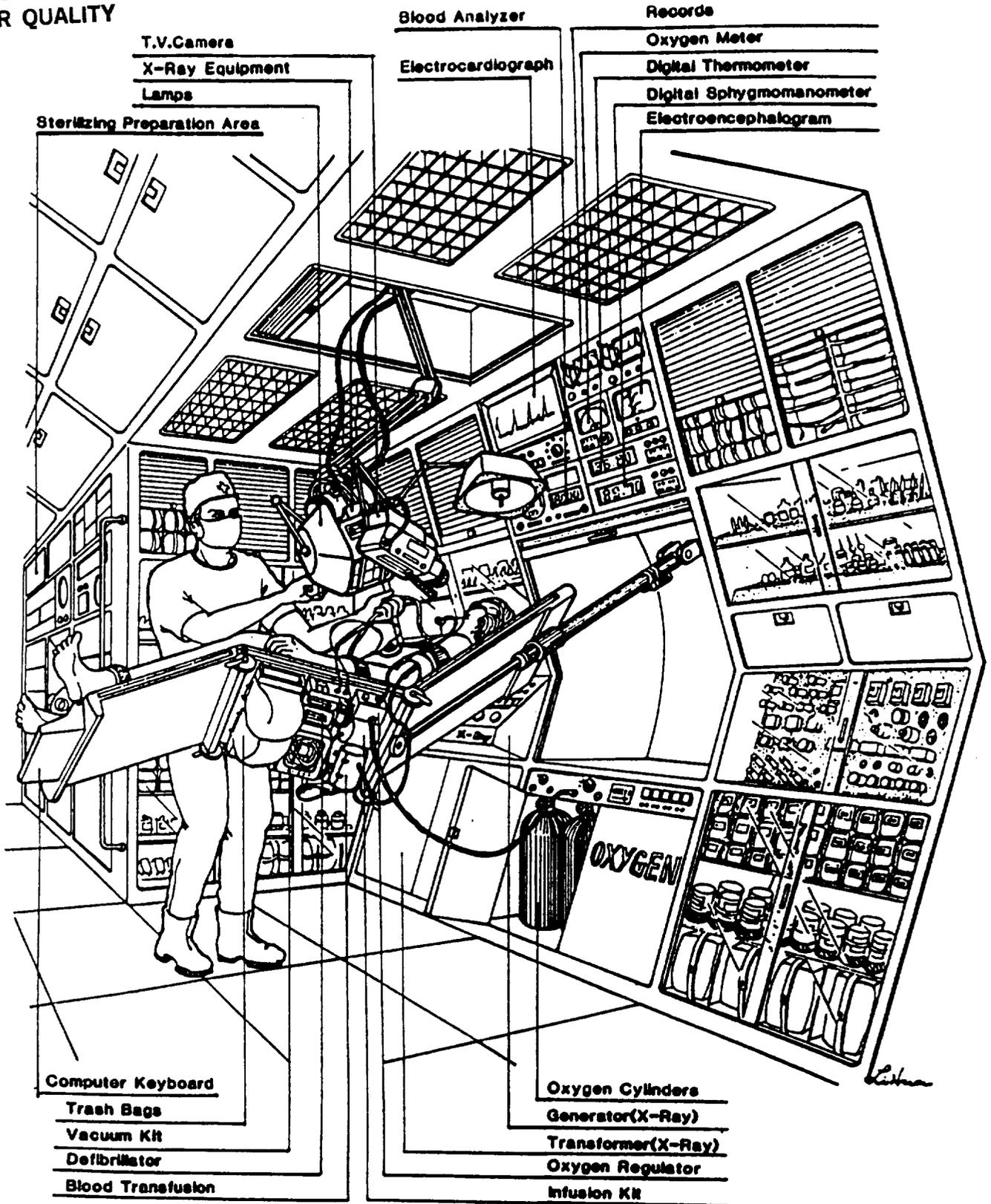


Figure 8.6.2 HMF for *Space Station Freedom* (Concept developed by NASA-JSC Medical Sciences Space Station Working Group and the University of Houston College of Architecture/SICSA).

8.7 Personal Quarters

Sleeping volume will increase over *Space Station Freedom* volumes because the crew must sleep horizontally and cannot sleep on the walls and ceiling.

As the mission becomes longer, the need for privacy increases. For long duration missions, dedicated, private crew quarters shall be provided for each crew member with sufficient volume to meet the following functional and performance requirements (NASA-STD-3000, 1987):

1. Sleeping
2. Storage (Personal and Operational)
3. Desk
4. Computer/Communication
5. Trash Storage
6. Personal Grooming/Dressing
7. Convalescence
8. Off-duty Activities (Reading)
9. Access to Storage

The internal dimensions of the crew quarters shall be sufficient to accommodate the largest crew member of the U.S. 95th percentile (Figure 8.1.2). The entrance/exit shall be sufficiently large enough to allow contingency entry by an EVA suited crew member (NASA-STD-3000, 1987). Table 8.7.1 shows the volume calculations for the crew quarters.

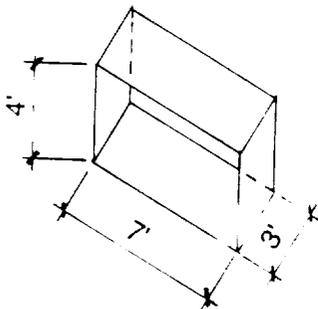
Crew quarters should have two-way audio/visual/data communication systems between the crew quarters, other module areas and the ground. The system should also have the capability of alerting the crew quarters occupant in an emergency (NASA-STD-3000, 1987).

Independent lighting, ventilation and temperature controls should be provided in crew quarters and should be adjustable from the sleeping area (NASA-STD-3000, 1987).

The noise levels in the crew quarters should be as low as possible during sleep periods. This can be accomplished through proper placement of the crew quarters within the habitat (NASA-STD-3000, 1987).

8.7.1 Crew Quarter Volumes

Function	Volume (cu. ft./cu. m.)
Sleeping**	85 / 2.4
Storage*	20 / 0.6
Personal Grooming/Dressing*	100 / 2.8
Temporary Storage*	2 / 0.06
Hardware (Controls and Lights)*	1 / 0.03
Reading (Included in Sleeping)	----
Accessories*	13 / 0.4
Computer/Communication**	30 / 0.8
Desk (Included in Computer/Communication)	----
Total	250 / 7.1



* NASA-JSC Crew Systems Review, 1988
 ** Packard, 1981

Table 8.7.2 below shows the total volume calculations for crew quarters for a crew of four (4), eight (8), twelve (12) and sixteen (16).

Table 8.7.2 Crew Quarters Volumes

# of Crew	Volume (cu. ft./cu. m.)
4	1000 / 28
8	2000 / 57
12	3000 / 85
16	4000 / 113

8.8 Personal Hygiene/Waste Management

Personal hygiene is important to both the psychological and physiological well-being of the crew. Facilities for performing personal hygiene functions must be available, properly sized and accessible.

Hygiene facilities should be designed with consideration for the following functions (NASA-STD-3000, 1987):

1. Skin Care
2. Shaving
3. Hair Grooming
4. Nail Care
5. Body Deodorant
6. Menstruation
7. Oral Hygiene

Good grooming can enhance self image, improve morale and increase the productivity of the crew members. Adequate and comfortable bathing and body waste management facilities have been high on the list of participants in various space missions. Some of the psychological factors involved in designing personal hygiene facilities are as follows (NASA-STD-3000, 1987):

1. Odor
2. Ease and Comfort of Use
3. Privacy
4. Feedback
5. Mission Duration

Objectionable body odors can rapidly build without adequate personal hygiene facilities. This is a predicted source of interpersonal conflict (NASA-STD-3000, 1987).

The personal hygiene facilities will not be used, or will be used infrequently, if they are awkward, uncomfortable or take an inordinate amount of time to use. This was a problem of the *Skylab* shower design (NASA-STD-3000, 1987).

It is desirable to have privacy for crew members for whole body and partial body cleansing (including donning and doffing of clothing).

Unfamiliar and inadequate facilities and environments can result in crew members falling into patterns of substandard hygiene. The results are likely to be reduced productivity and interpersonal conflict. Provision of full length mirrors, using a highly polished metal wall, or other means of feedback can help to maintain personal image and hygiene habits (NASA-STD-3000, 1987).

Shorter missions generally require less extensive personal hygiene facilities. However, for a Lunar base, a Mars spacecraft or base, facilities will need to be very extensive and comfortable for the crew to use.

Waste management system design should follow the following considerations (NASA-STD-3000, 1987):

1. Reliability and Maintainability
2. Ease of Use
3. Acceptance
4. Number of Facilities
5. Privacy

System servicing and repair are neither pleasant nor mission productive. Therefore, the system should be as reliable as possible and require a minimum of repair time.

The system should be simple and quick to use. The system should be available for emergencies such as vomiting or diarrhea. As a design goal, the facilities should be used like and require approximately the same amount of time for use as Earth facilities (NASA-STD-3000, 1987).

The body waste management facility must be both psychologically and physiologically acceptable to the crew members. It is recommended by NASA that one facility be provided for every four crew members. Also, defecation and urination facilities should provide both visual and auditory privacy for the user (NASA-STD-3000, 1987).

Figure 8.8.1 shows a design for a 1 1/2 rack personal hygiene/waste management facility for the *Space Station Freedom* (Bell & Trotti, 1986).



Figure 8.8.1 Personal Hygiene/Shower (Bell & Trotti, 1986).

For adaptation to a partial gravity environment, a 2 rack system will be required, as shown in figure 8.8.2, which may not require a microgravity handwasher.

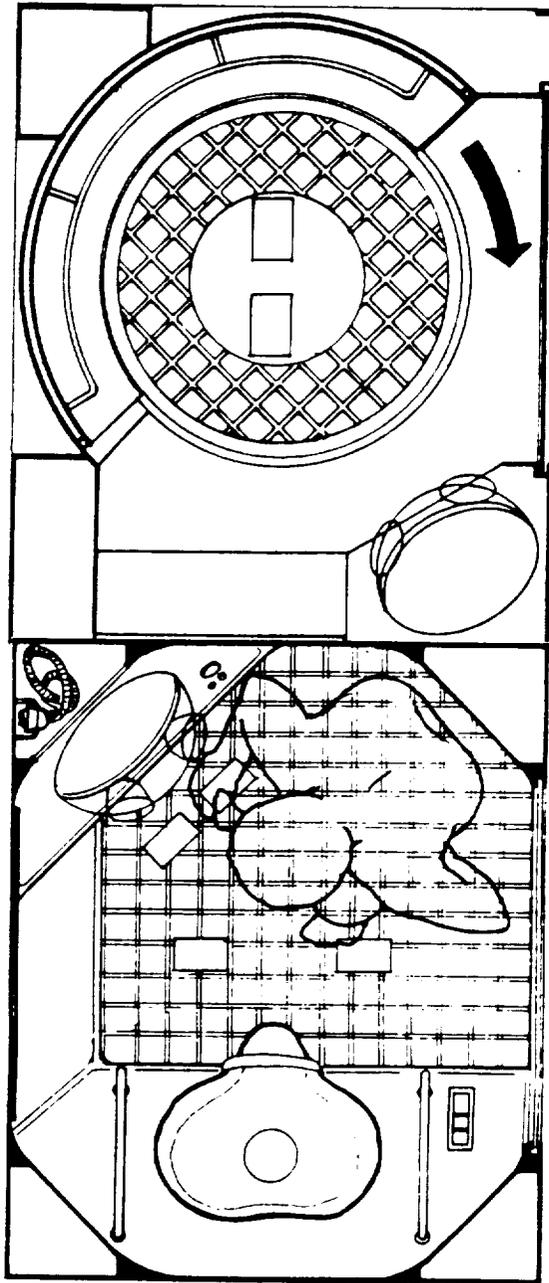


Figure 8.8.2 Personal Hygiene/Shower (Adapted from Bell & Trotti, 1986).

Table 8.8.1 summarizes volume requirements based on the assumption that one facility is required for every four crew members, and that a two rack facility takes up a volume of 165 ft.³ (each rack is approximately 82 ft.³, as stated previously).

Table 8.8.1 Personal Hygiene/Waste Management Volumes

# of Crew	Volume(cu. ft./cu. m.)
1 - 4	165/ 5
5 - 8	330/ 9
9 - 12	495/ 14
13 - 16	660/ 18

8.9 Laundry

A clothes washer/dryer will be necessary for long duration space settlement because it will be inefficient to dispose of or resupply clothing. A clothes washer/dryer has been estimated for the *Space Station Freedom* at 4' x 1' x 4' (1.2m x 0.3m x 1.2m) or 16 ft.³ (0.45m³) (Lewis, 1983). It is not anticipated that a washer/dryer in partial gravity will be any larger.

Figure 8.9.1 shows the dimensions of the washer/dryer with a 3' (0.91m) by 8' (2.44m) access area to adapt it to a partial gravity situation. The volume of the laundry including equipment and access area is 128 ft.³ (3.6m³).

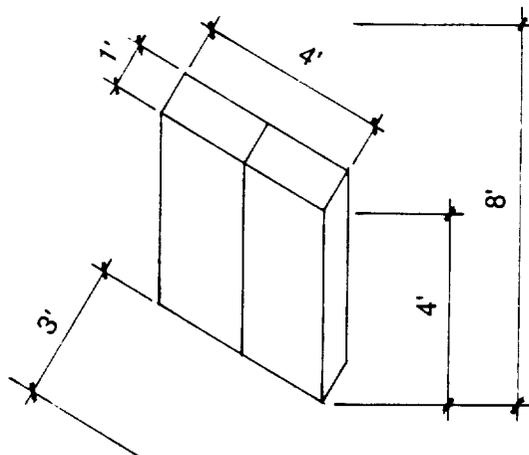


Figure 8.9.1 Laundry Facility

One (1) laundry facility will be required for every eight (8) crew members. Table 8.9.1 shows volumetric requirements for crews of eight (8) and sixteen (16).

Table 8.9.1 Laundry Facility Volumes

<u># of Crew</u>	<u>Volumes(cu. ft./cu. m.)</u>
1 - 8	128/ 4
9 - 16	256/ 7

8.10 EVA Storage

Extra Vehicular Activity (EVA) suit storage should provide at least one spacesuit for every crewmember in case of an emergency. EVA suit storage has been estimated as being 53 ft.³ (1.5m³) per suit (Bell & Trotti, 1988). Table 8.10.1 shows volume estimations for crews of four (4), eight (8), twelve (12) and sixteen (16) based on the above volume requirements.

Table 8.10.1 EVA Storage Volumes

<u># of Crew</u>	<u>Volumes(cu. ft./cu. m.)</u>
1 - 4	212/ 6
5 - 8	424/ 12
9 - 12	636/ 18
13 - 16	848/ 24

8.11 Laboratory/Work Space

Laboratory/work space is a volume that can only be calculated when the exact function of a facility is determined. Therefore, for the purposes of this study, the laboratory/work space will be looked at generically, and volumes will be determined based on a study that has speculated on the contents of a lunar base laboratory facility.

The concept of a discipline-oriented facility, either as a dedicated or shared laboratory, has been proposed and adapted on Earth and in space for numerous applications. In

principle, a dedicated laboratory on the Moon would provide the following advantages (Batelle, 1987):

1. Dedicated space to allow focused experiments.
2. Dedicated common facilities and equipment for common interest.
3. Physical isolation from other operations.

A variety of life science experiments are envisioned for lunar surface applications. Initially, life science experiments on the Moon might be directed at gaining experience with relatively simple biological systems and research techniques operating in 1/6th gravity.

A Life Science Facility (LSF) would require capabilities in biochemistry, analytical chemistry, cell biology, plant physiology and microbiology. The LSF would be organized into five basic laboratory experiments (Batelle, 1987):

1. General Laboratory
2. Analytical and Biochemical Laboratory
3. Plant Growth Facility
4. Microbiological/Algal Growth Facility
5. Waste Recycling Laboratory

Each laboratory would have separate environmental control and information systems and would have the capability of being closed off for highly sensitive experiments or contingency events (Batelle, 1987). Table 8.11.1 shows the five basic laboratory functions with volumes and equipment requirements.

Each laboratory would contain an array of equipment and instrumentation that would support the LSF (Batelle, 1987). Table 8.11.2 illustrates the physical characteristics for key equipment and instrumentation.

Other scientific functions will be required based on the nature of experimentation performed at the base. Therefore, the volume for a laboratory can only be calculated as specific requirements for space missions are laid out. The previous illustrates volumes for a possible

Facility/Elements	Functional Description	Physical Characteristics and Utility Requirements
<u>General Laboratory</u>	Serves as the support facility for inspection, preparation, handling storage, and biochemical analysis of samples and products of experiments within the overall lab. Laboratory includes provisions for Class I, III, and III operations.	This facility will require approximately 50 m ³ including space allocations for crew. About 1000-1500 kg of equipment will occupy this volume. Average power demands could reach 3500 watts. The refrigerator/freezer and autoclave are large power consumers.
<u>Analytical and Biochemistry Facility</u>	This facility provides additional analytical support and instrumentation to support life science experiments. Like the general laboratory, provisions will be made for sterile handling of biological samples, toxic or volatile substances, and radioisotopes	The internal facility volume of 40 m ³ includes about 1000-1500 kg of equipment. Power requirements are anticipated to be in the range of 2500-3500 watts.
<u>Plant Growth Facility</u>	This facility is planned for selective breeding and a growth of plants using hydroponics, soil, aeroponics and/or misting culture techniques. Investigations would span a number of species and involve investigations on lighting; fertilizing; productivity; radiation; harvesting; and atmospheric monitoring and control system techniques.	The 65-m ³ facility will have a minimum equipment mass of 1500-2500 kg. Access to a centralized gas and water supply are assumed. Average power demands are about 7500 watts.
<u>Microbiological/Algal Growth Facility</u>	Unicellular organisms (algae, yeasts, bacteria) are to be cultured in this facility. Among the experiments to be conducted are subsystem and system performance characteristics; optimization of growth conditions (i.e., algae type, lighting, nutrient cycles) and operational tests to resolve specific problems (fouling/foaming; algae preservation, gas-liquid and liquid-solid separation, etc.)	Volume requirements for this facility are on the order of 50 m ³ . Equipment mass ranges from 1000-1500 kg with power demands averaging 3000 watts. Access to a centralized water and CO ₂ supply is assumed.
<u>Waste Recycling Facility</u>	Research in this facility focuses on the pretreatment and digestion/conversion of waste and the recycling of various products to meet other subsystem needs. Research and evaluation of a variety of waste streams will involve (1) subsystem testing and verification of pretreatment processes, chemical/biological conversion processes, and monitoring and control, and (2) long-term performance and parametric studies on a fully-integrated system.	Average power demands for this 80-m ³ facility would be 2500-3500 watts. Initially, operations are likely to be in the batch mode. Equipment mass would approach 1000-1500 kg.

Table 8.11.1 Lunar Life Science Laboratory (Batelle, 1987).

Equipment (Number of Items)	Mass (kg)	Dimensions (hwxl, cm)	Volume (m ³)	Average Power (Watts)		
				<100	100-500	500-1000 >1000
<u>GENERAL FACILITY</u>						
Computer Station	500	300x100x75	2.25	--	--	x
High-Speed Centrifuge	15	32x38x48	.058	--	x (100)	--
Autoclave	10	33x34x42	.047	--	x	--
Incubators(6)	18	42x34x28	.040	x	--	--
Refrigerator/Freezer(1)	50	86x61x60	.31	--	x	--
Glove Boxes(1)	73	94x96x76	.69	--	x	--
Sink/Dishwasher	82	88x61x65	.35	--	x	--
Drying Oven	59	76x69x66	.35	--	--	x (1900)
Microscopes	2.9	37x23x28	.024	x (15)	--	--
Radioactive Material Storage	113	140x110x80	1.2	--	x	--
Balances	8.8	27x19x30	.015	x	--	--
pH/specific ion meters	2.1	14x24x31	.01	x (1)	--	--
Fume Hood	123	120x120x56	.80	x	--	--
Biohazard Hood (Laminar flow)	288	150x130x92	1.8	x	--	--
Videocamera (with generator)	0.5	--	.01	x (6)	--	--

Table 8.11.2 Lunar Life Science Laboratory (Batelle, 1987).

Equipment (Number of Items)	Mass (kg)	Dimensions (hxxwxl, cm)	Volume (m ³)	Average Power (Watts)		
				<100	100-500	500-1000
<u>ANALYTICAL AND BIOCHEMISTRY FACILITY</u>						
Gas Chromatograph/ Mass Spectrometer	127	152x76x64	.74	--	--	--
High-Performance Liquid Chromatograph	27	28x41x33	.038	--	x (200)	--
UV/Visible Spectro- photometer	34	25x62x64	.099	x	--	--
Ultra Centrifuge	6	27x21x29	.016	x (100)	--	--
Liquid Scintillation Counter	48	42x28x49	.058	--	x	--
Nucleic Acid Synthesizers	45	41x28x51	.058	--	x (115)	--
Scanning Electron Microscope	163	110x110x122	1.4	--	--	x
Atomic Absorption Spectrophotometer	100	63x51x58 burner accessory	.48 .07	x	--	--
Peptide Sequencer	23	90x90x50	.40	--	x	--
Biochemistry equipment (including electrophoresis, isoelectric-focusing, column chromatography, and fraction collection	300-500	300x100x100	3	--	x	--

Table 8.11.2 (Continued).

Equipment (Number of Items)	Mass (kg)	Dimensions (hwxl,cm)	Volume (m ³)	Average Power (Watts)		
				<100	100-500	500-1000 >1000
<u>MICROBIAL/ALGAL GROWTH FACILITY</u>						
Fermentors(4)	135	200x170x75	2.6	--	x	--
Lighted Algal Tanks(2)	45	120x75x50	.45	--	--	x
Incubators(6)	80	21x11x36	.008	x (225)	--	--
Lyophilizer	25	37x37x42	.057	--	x	--
Refrigerator/Freezer(1)	122	150x75x80	.90	--	x (480)	--
<u>PLANT GROWTH FACILITY</u>						
Homogenizer	11	34x34x120	.14	--	--	--
Generator	3	10(Dia)x36	.0028	--	x	--
Transducer					(375 peak)	--
Small-Capacity Growth Chambers(12)	68	120x80x75	.75	--	x	--
High-Capacity Growth Chambers(2)	430	200x200x75	3.3	--	--	x
Refrigerator/Freezer(2)	50	86x61x60	.31	--	x	--
Computer Station	500	300x100x75	2.25	--	--	x

Table 8.11.2 (Continued).

Equipment (Number of Items)	Mass (kg)	Dimensions (hwxl,cm)	Volume (m ³)	Average Power (Watts)		
				<100	100-500	500-1000 >1000
<u>WASTE RECYCLING FACILITY</u>						
Anaerobic and Aerobic Digestion Tanks(6)	45	250x60x60	.90	--	x	--
Glove Box(1)	73	94x96x76	.69	--	x	--
Haber-Bosch Units(2)	90	75x260x75	1.46	--	x	--
Condensors(2)	34	200x150x80	2.4	x	--	--
Waste Storage Tanks(2)	45	35(Dia)x58	.055	x	--	--
Pretreatment Tanks(2)	45	35(Dia)x58	.055	x	--	--

Table 8.11.2 (Continued).

Life Science Facility, which will only be a part of any partial gravity space mission. Section 9.0 in the NASA Man-Systems Integration Standards (NASA-STD-3000, 1987) gives specific design requirements for workstations and will be a great asset to the design of a space laboratory, when that space is defined.

8.12 Maintenance/Work Area

A maintenance/work area will consist of space to perform repair operations and storage for tools and equipment. The maintenance/work area for the *Space Station Freedom* has been designed to fit into two (2) racks, which will take up a volume of 165 ft.³ (4.7m³), excluding equipment access, as shown in figures 8.12.1 and 8.12.2 (NASA/JSC Crew Systems Review, 1988). This volume, with a 3' deep by 7' wide by 8' high equipment access area, would bring the total volume to 330 ft.³ (9.5m³) for a crew of eight (8). This volume would double for a crew of sixteen (16). Table 8.12.1 shows the maintenance/work area volumes for a crew of eight (8) and sixteen (16).

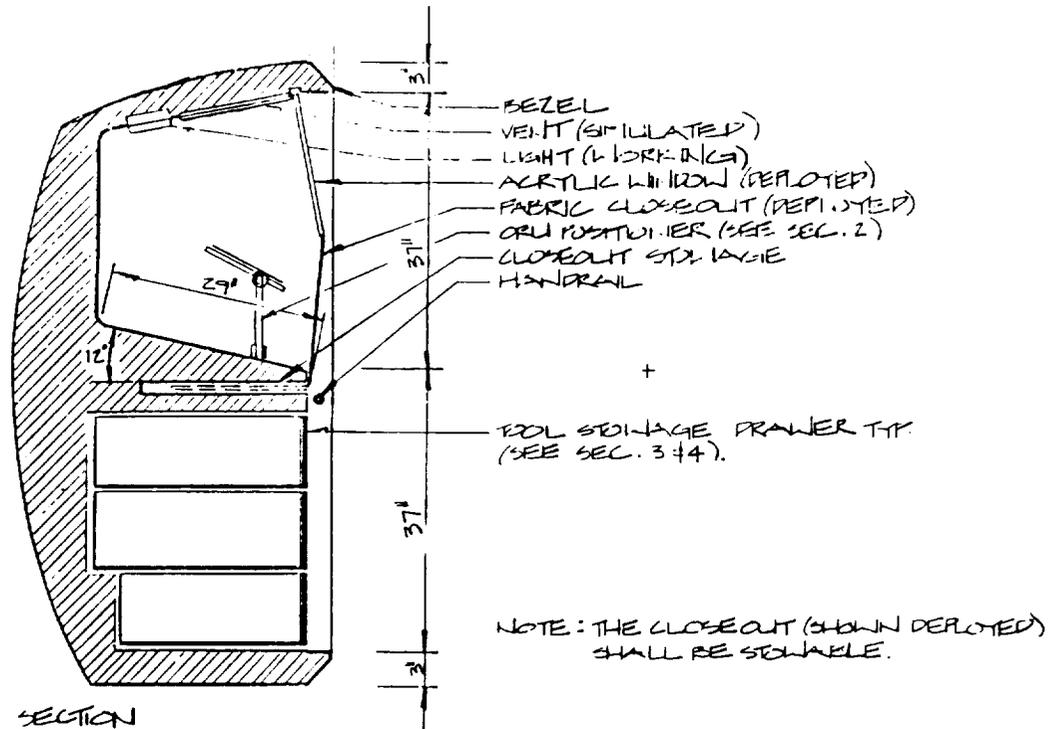


Figure 8.12.1 Maintenance/Work Area (NASA/JSC Crew Systems Review, 1988).

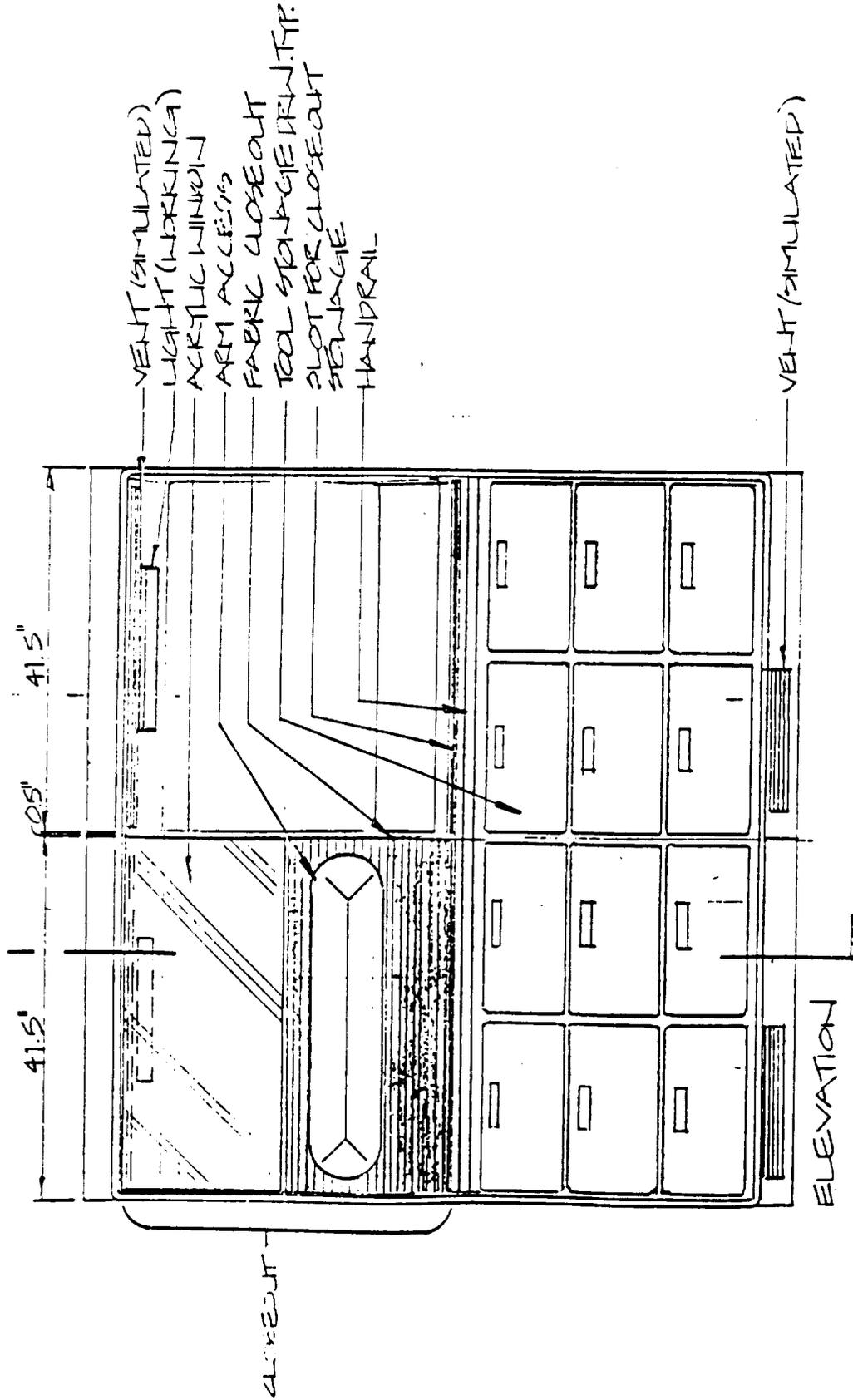


Figure 8.12.2 Maintenance/Work Area (NASA/JSC Crew Systems Review, 1988).

Table 8.12.1 Maintenance/Work Area Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 8	330/ 9.5
9 - 16	660/ 19.0

The volumes could be higher due to the remoteness of a lunar Base, Mars spaceship or base, but data on this is unknown.

8.13 Circulation

Circulation, for this study, has been calculated as dedicated circulation space. In other words, circulation is a clear, unobstructed path that can be used in an emergency situation. Equipment access and circulation within spaces has been estimated into the volumes of the spaces themselves. Dedicated circulation is hallway passage, circulation through nodes and vertical circulation (stairs and ladders).

Dimensions of circulation paths, as stated previously, should be at least 4'-6" (1.37m) wide by 8'-0" (2.44m) high times the length of the module, node, or whatever the passage is through. Generally, there must be a clear circulation path throughout the entire length of a module. As an example, for a two story module, 20'-0" (6.1m) diameter by 45'-0" (13.7m) length, dedicated circulation is 3250 ft.³ (92m³) or approximately 25% of the total volume. For the previous example, the volume was calculated in the following manner:

$$4'-6" \times 8'-0" \times 45'-0" \times 2 \text{ (floors)} = 3250 \text{ ft.}^3$$

Vertical circulation is still a question and point of debate in an partial gravity environment because it is uncertain as to the distance between risers (steps). Due to the lower gravity level, initially, humans will be able to leap higher than in Earth conditions. However, in the long run, it is unsure as to whether a human's muscles will atrophy and steps similar to those on Earth will be needed. Whichever

type vertical circulation is needed, it will need to be space efficient, like the stairs illustrated in figure 8.13.1.

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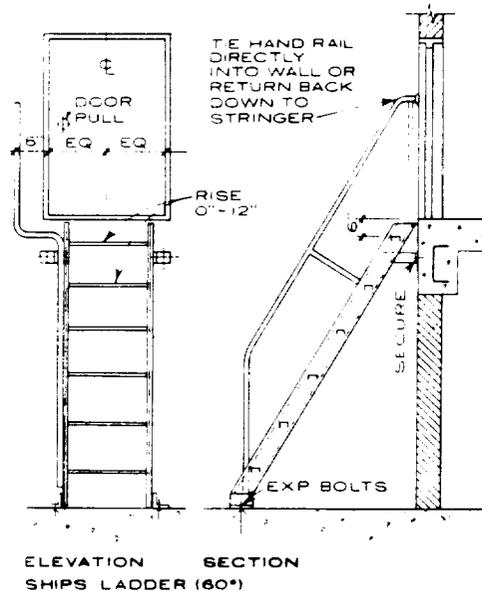


Figure 8.13.1 Ships Ladder (Packard, 1981).

The ratio of circulation to usable space varies based on the module size and is discussed in section 10.1.

8.14 ECLSS/Storage

An Environmentally Closed Life Support System (ECLSS), as envisioned now, will mainly serve the purpose of recycling water and oxygen. It is estimated that water can be recycled at 90% efficiency while oxygen can be recycled at 95% efficiency (Sturm, 1988). Volume for an ECLSS/Storage area can be calculated by using the following equations:

Consumables Storage (Sturm, 1988):

$$\text{Volume (m}^3\text{)} = (5.43 \times \text{CN}) + (0.007 \times \text{Vol})$$

Regenerative Systems (Sturm, 1988):

$$\text{Volume (m}^3\text{)} = (0.225 \times \text{CN}) + 2.35 + \text{Vol}/200$$

Where:

CN = Crew Number

Vol = Habitat Volume

Table 8.14.1 shows volume calculations for ECLSS storage and consumables storage for a crew of four (4), eight (8), twelve (12) and sixteen (16) for a habitat volume of 12,500 ft.³ (350m³).

Table 8.14.1 ECLSS/Storage Volumes

# of Crew	Volume (cu. ft./cu. m.)
1 - 4	1060/30
5 - 8	1830/52
9 - 12	2630/75
13 - 16	3430/97

Volume of the habitat should be calculated from all other sections before calculating and adding in volume for the ECLSS/Storage area.

8.15 Safe Haven

The safe haven is a retreat for the crew from high doses of radiation caused by solar flares. The safe haven should be equipped with all the necessities for survival for a period of a few hours to a few days, depending on the duration of the solar flare activity.

A safe haven for a planetary surface could be incorporated into the base itself, as opposed to having a separate entity, depending on how the base is shielded. For a Mars vehicle, it will probably be cheaper to provide a separate entity for the safe haven rather than shielding the entire habitat.

In either case, sufficient volume for the entire crew should be allocated to ensure safety during peak solar events. Volume requirements for a safe haven are based on a study conducted by Breeze (1961) who found that humans need at least 260 ft.³ (7.5m³), from a psychological standpoint, for isolation periods of less than two months. Therefore, a safe haven volume can be calculated by the following equation:

$$\# \text{ of Crew} \times 260 \text{ ft.}^3 = \text{Safe Haven Volume}$$

Table 8.15.1 shows the volumes for a safe haven for crews of four (4), eight (8), twelve (12) and sixteen (16).

Table 8.15.1 Safe Haven Volumes

<u># of Crew</u>	<u>Volumes(cu. ft./cu. m.)</u>
1 - 4	1040/ 29.5
5 - 8	2080/ 60.0
9 - 12	3120/ 88.5
13 - 16	4160/118.0

PART III APPLICATIONS TO A LUNAR BASE DESIGN

Part III of this report will address the issues of how the design requirements of a partial gravity habitat are adapted to a specific environment. In this case it was decided to apply them to a lunar base.

Part III covers such issues as mission scenario, masses through LEO (Low Earth Orbit), volume calculations, interior architecture and layout, exterior architecture and configuration, radiation protection issues, and site requirements and configuration.

9.0 Introduction

9.0 Introduction

The purpose of defining the requirements for a partial gravity habitat facility is to serve as a basis from which a design may be developed, and to provide an example of how to use these requirements. We chose to apply these requirements to the design of a lunar base.

Throughout the study, ways in which the 1/6 g of the Moon affected the design were noted. This allowed us to apply the standards we have developed to an actual design problem, providing a better understanding of the procedure needed to design for any partial gravity environment.

In light of the work done in Parts I & II of this study, a scenario was developed as a guideline for the lunar base proposal. This scenario was cross referenced with a scenario developed by Lockheed Engineering and Management Services Company in Houston, Texas, for the build up of a permanently manned lunar base. This was done to ensure accuracy in: time line depiction; masses through LEO (Low Earth Orbit); rate of growth; and to maintain an overall sense of feasibility. For the detailed scenario, see appendix A. The Lockheed scenario used was originally developed for NASA Johnson Space Center in Houston, Texas.

Our design group performed area calculations to determine the correct volume requirements for growth of the lunar base as dictated by the scenario. Studies of the interior architecture were also made to ensure the most practical use of the space provided. These studies were made based on most usable cross sectional space of a cylindrical module, circulation patterns, and functional layout.

The exterior architecture was also studied with respect to module configuration, phasing of growth, and how connections were made between the modules.

Radiation protection also became a primary design driver in this study. It was deemed necessary to cover the habitat modules of the base with 4.5 meters of regolith to provide full protection from solar flare events (it has since been suggested that only .5 meters of regolith may be required to provide adequate protection). Issues of how to protect the initial base while allowing for phased coverage were looked at as well as possible support structures for the regolith.

Finally, the issues of the site were addressed. Issues such as where the facility is located on the lunar surface, and also the layout within the facility itself.

Assumptions

The following are assumptions regarding technologies which will be available when the project is to begin. There is an assumed 570 metric tons of mass allowed through LEO (Low Earth Orbit)(see table 9.1.1). There will be heavy lift launch capability for the modules which are 6.7m diameter by 17.2m length, weighing roughly 35 metric tons. The modules will be launched either fully or partially outfitted depending on the capabilities of the lunar lander and moving vehicles on the Moon.

9.1 Scenario

The scenario used was originally developed by Lockheed Engineering and Management Services Company in Houston, Texas, and was adapted to better serve our needs.

The following is a condensed version of the scenario used for the planning of the Lunar Base proposal. For a monthly breakdown of the scenario, please refer to appendix A.

The functions to be performed by the lunar base are primarily industrial and experimental sciences. The base will serve as a LLOX (Lunar Liquid OXYgen) production facility and fueling station, and center for further study of the Moon and its evolution along with the solar system and universe. It will be used to develop and test new materials using the in situ resources.

Between January 1998 and August 2003, there are a scheduled 18 unmanned lunar missions. These missions are to conduct a number of orbital scientific experiments, to have several lander and sample return missions, and to place equipment on the surface for later use. These missions are all preparatory work for later missions to come.

The first eight months of the year 2004 are also spent landing supplies and equipment on the lunar surface. The first crew of four does not arrive until August of 2004. The equipment which is landed in 2004 includes such things as 1.5 Mw power plants, cranes and regolith moving equipment, plant facilities for the production of LLOX (Lunar Liquid OXYgen) using a fluorine reduction process, a work and habitat facility, science equipment, and an unpressurized rover.

In February 2005 there is a crew change out and a resupply of food. There is an increase in activity on the Lunar Base now--more equipment is being launched from Earth, mostly telescopes and communications equipment. There is also another crew change and food resupply which occurs in August. In October of 2005 another habitat facility is landed along with all amenities required. Another LLOX plant is added to the base, yet fuel is still being supplied from Earth.

In February of 2006, there is another crew change and food resupply. Figure 9.1.1 is a diagram of the crew changes which occur. From this point on, the crew changes will become more complex as they get staggered, thus leaving more crew members at a time on the surface, figure 9.1.1 will serve as a guide to the number of crew members and their frequency of change.

During the year 2006, more science equipment is landed and work is begun building an agriculture facility using cast basalt building blocks in an igloo fashion. Between May and June 2006, more members of the structural system are landed, along with another 1.5 Mw power plant, an unpressurized vehicle, and fluorine for the LLOX facilities.

In August there is a crew change, and in September there is another habitat facility landed.

The year 2007 is spent primarily transporting supplies and resupplies for the LLOX facility along with an additional 3 1.5 Mw power plants. There are two crew changes, one in February and the other in August. Life support facilities for the third habitat facility are also completed in the early part of 2007.

By 2008, it is time to resupply many of the life science facilities as well as other experiment and science oriented facilities. There is the usual crew change in February and August, and food resupply. Manned missions on the surface become more frequent and more regolith moving equipment is landed. There are an additional three 1.5 Mw power plants added along with more LLOX liquefaction plants.

At this point, the scenario begins to grow at a tremendous rate due to the use of lunar materials. The lunar materials are used for production of LLOX, construction materials, plant growth etc. By using lunar derived LOX, there is no longer a need to bring O₂ from the Earth for use on the lunar surface or for fueling other crafts for use in the Earth-Moon system, or the Earth-Mars system.

The use of lunar materials for construction falls mainly into the use of basalts. Through the processes of casting, sintering or even microwaving, basalt becomes a very usable and strong material. These materials in turn are used in the fabrication of habitable or storage structures, tools and paved surfaces respectively. By using lunar grown foods, the demand for Earth supply will be lessened. This is a very important step in making the Lunar Base more self-sufficient.

The following chapters of Part III deal with issues of interior architecture, exterior architecture and site requirements.

For masses to the lunar surface and crew change frequency see tables 9.1.2 and 9.1.3 respectively.

Lunar Evolution Case Study

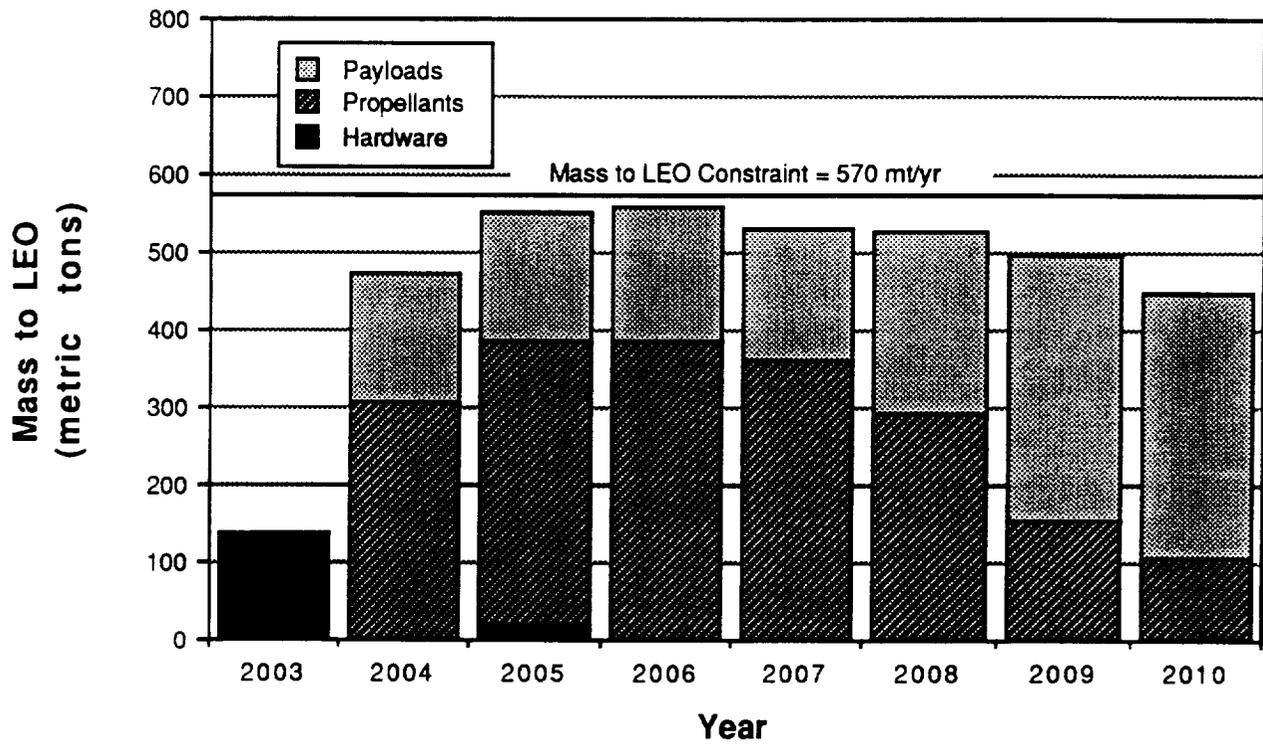


Table 9.1.1 Mass to LEO

Lunar Evolution Case Study

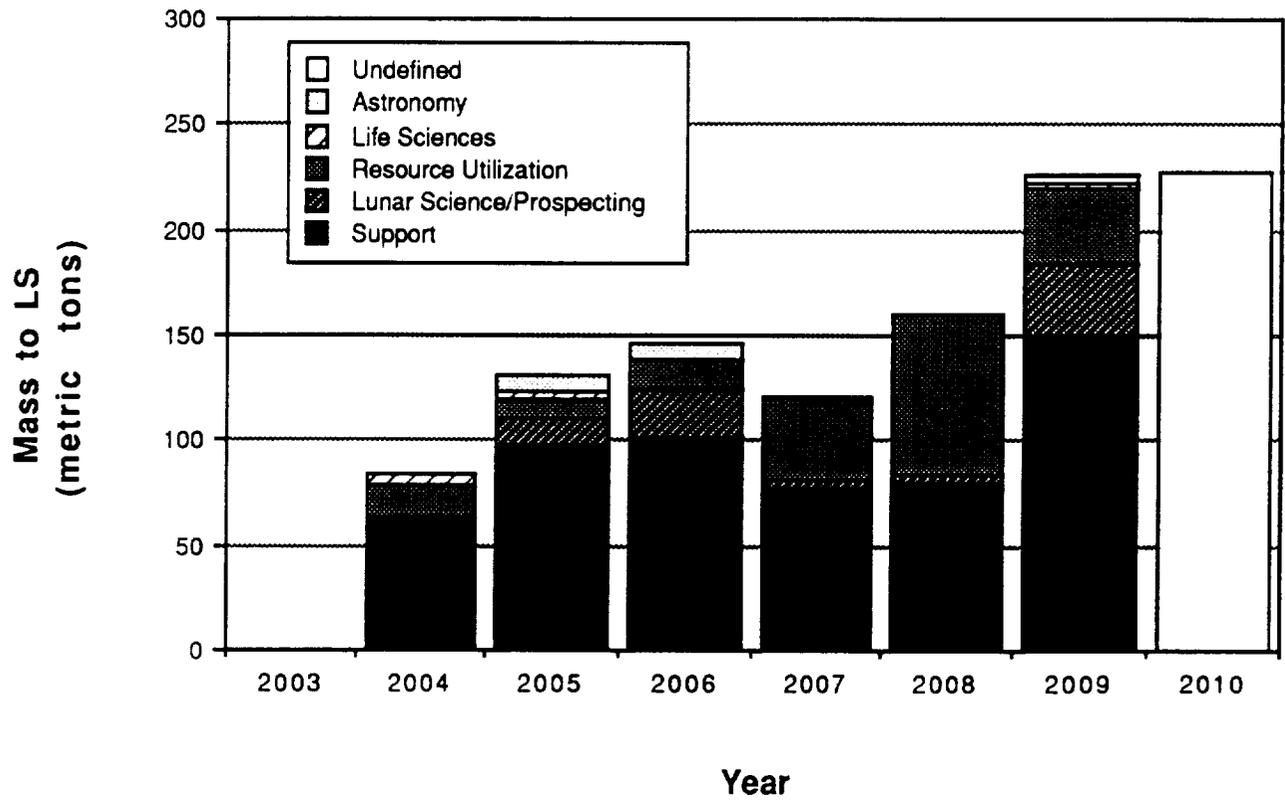


Table 9.1.2 Mass to lunar surface

Lunar Evolution Case Study

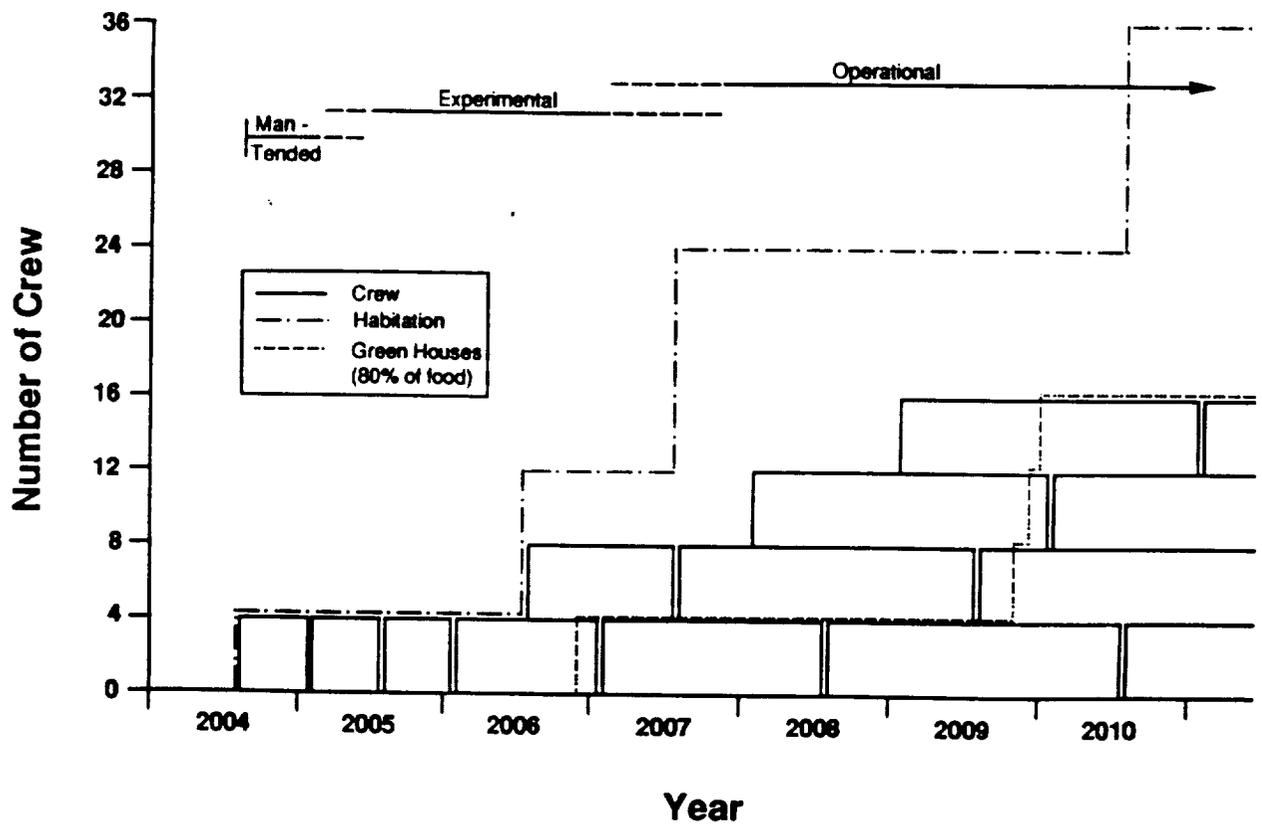


Table 9.1.3 Crew change frequency

10.0 Volume Calculations

10.0 Introduction

The following takes the results of the volume study in section 8.0 and applies it to a Lunar Base scenario to illustrate how the volumes can be used. The volumes calculated investigate the amount of habitat space, excluding laboratory, needed for a crew of twelve (12) that will eventually expand to a crew of thirty-six (36).

10.1 Calculations

A crew of twelve (12) will require two (2) racks for appliances and three (3) racks for food storage. Therefore, a volume of 830 ft.³ (23.5 m³) will be required for equipment and access space, as shown in figure 10.1.1.

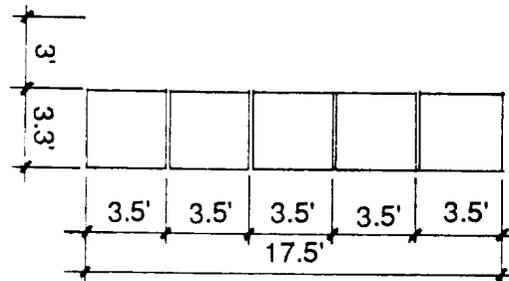


Figure 10.1.1 Galley Layout for Crew of Twelve (12).

The contingency food and trash storage for the crew with a 90-day resupply cycle is calculated as follows (see section 8.2):

$$(0.68 \text{ ft.}^3 + 0.1 \text{ ft.}^3) \times \# \text{ of Crew} \times \text{Resupply Cycle}$$

or

$$(0.68 \text{ ft.}^3 + 0.1 \text{ ft.}^3) \times 12 \times 90 = 378 \text{ ft.}^3$$

Therefore, 378 ft.³ (10.7 m³) is required for contingency food and trash storage.

Dining/wardroom volume has been calculated to be 1600 ft.³ (45 m³), as shown in figure 8.3.2 and table 8.3.1.

A recreation area for the crew has been estimated at 4080 ft.³ (115 m³), as shown in table 8.4.4.

An exercise area has been estimated at approximately 700 ft.³ (20 m³), as shown in figure 8.5.1.

The Health Maintenance Facility (HMF) for a Lunar Base has been estimated at 480 ft.³ (14 m³). As the base expands, the facility will become more extensive. How extensive is unsure at this point, so a volume of 480 ft.³ (14 m³) will be used for every crew of twelve (12).

Personal quarters have been estimated to be 250 ft.³ (8 m³) for each crew member. Therefore, volume for the entire crew of twelve (12) will be 3000 ft.³ (85 m³), as shown in table 8.7.2.

Personal hygiene/waste management facilities have been designed at a volume of 165 ft.³ (5 m³) per crew of four (4). Therefore, for this Lunar Base, a volume of 495 ft.³ (14 m³) will be required (see table 8.8.1).

Laundry facilities for a crew of twelve (12) has been calculated to be 256 ft.³ (7 m³), as shown in table 8.9.1.

EVA suit storage has been calculated to be 636 ft.³ (18 m³), as shown in table 8.10.1.

Maintenance/work area volumes are shown in table 8.12.1 to be 660 ft.³ (19 m³) for a crew of twelve (12).

At this point it is necessary to estimate the size of the module in order to arrive at the volume required for circulation. The previous volumes add up to approximately 13,000 ft.³ (370 m³). If we assume circulation to be approximately 25% (see section 8.13) of this volume, for purposes of sizing the habitat module, and allow a small contingency of 5 to 10% for the ECLSS, a module size of 22' (6.7 m) by 56.5' (17.2 m) (two-level interior configuration), with a volume of 19,375 ft.³ (550 m³), can be used.

Using the previously sized module and the requirements for the circulation from section 8.13, a dedicated circulation volume of 4070 ft.³ (115 m³) will be required.

If we assume the water and oxygen storage to be outside the module for a Lunar Base, the ECLSS equipment can be calculated to take up 275 ft.³ (7.8 m³) by the following equation (see section 8.14):

$$\text{Volume} = (0.225 \times \text{CN}) + 2.35 + \text{Vol}/200$$

or

$$(0.225 \times 12) + 2.35 + 550/200$$

A dedicated safe haven for a Lunar Base can be eliminated by covering the habitation modules with regolith; therefore, eliminating redundant space.

The remaining 1900 ft.³ (54 m³) is used for the volume of the structure, wall partitions and mechanical chase space as well as contingency storage.

Table 10.1.1 summarizes the volume calculations for the Lunar Base habitat for a crew of twelve (12).

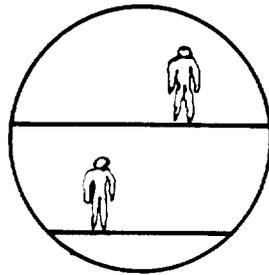
Table 10.1.1 Lunar Base Habitation Volume

<u>Function</u>	<u>Volume (cu. ft./cu. m.)</u>
Galley	830/ 23.5
Contingency Food & Trash	378/ 10.7
Dining/Wardroom	1,600/ 45.0
Recreation	4,080/ 115.0
Exercise	700/ 20.0
Health Maintenance Facility	480/ 14.0
Personal Quarters (250 ft. ³ x 12)	3,000/ 85.0
Personal Hygiene/Waste Management (3)	495/ 14.0
Laundry	256/ 7.0
EVA Storage	636/ 18.0
Maintenance/Work Area	660/ 19.0
Circulation	4,070/ 115.0
ECLSS	275/ 7.8
Total	17,460/494.0

When the crew of twelve (12) expands to a crew of thirty-six (36), the volume of the habitat space will triple to bring the total habitat volume to 53,580 ft.³ (1518 m³). The crew can be housed in three (3) module that are 22' (6.7 m) by 56.5' (17.2 m), with a total volume of 58,125 ft.³ (1650 m³).

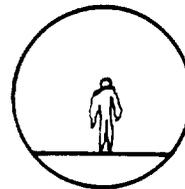
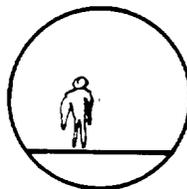
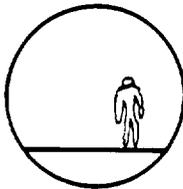
If *Space Station Freedom* size modules are used for a Lunar Base, the number of modules required will increase by about a factor of three. The *S. S. Freedom* modules are approximately 15' (4.5 m) diameter by 45' (13.7 m) in length, with a volume of approximately 7,000 ft.³ (200 m³). Since the volume required for circulation is about 1620 ft.³ (46 m³), three (3) modules would probably be required for the same crew of twelve (Figure 10.1.1), thus increasing the weight of the habitation modules. Therefore, the crew of thirty-six would require approximately nine (9) *Space Station Freedom* size modules for habitation.

* Weights are for primary structure only (Duke & Keaton, 1986).



Volume
550 m³

Weight*
9,350 kg



Volume
675 m³

Weight*
21,600 kg

Figure 10.1.2 HLLV vs. *Space Station Freedom* Modules

There is added difficulty in landing and maneuvering an HLLV module on the lunar surface, but is not a problem for a Mars spacecraft. However, if the landers and vehicles are available, as per our assumption in section 4.0, this will not present a problem, except for fuel consumption.

11.0 Interior Architecture

11.0 Introduction

The interior architecture is derived by determining the interior configuration of the human habitation areas (i.e., one-level like *Space Station Freedom* modules, or two-level HLLV-sized modules like those discussed in section 11.1), studying the circulation patterns within and out of the modules, and finally, arriving at a functional layout based on the previous as well as functional adjacencies. The interior architecture will become optimum if the proper volumes (discussed in section 8.0) are coupled with the process of deriving the interior architecture, therefore creating an interior arrangement that works functionally as well as psychologically for the crew.

The sectional configurations are evaluated based on size, circulation patterns and overall space efficiency. From a module study conducted by our group in the fall semester 1988, it was concluded that a 22' (6.7 m) diameter module with two-levels would be the most space efficient size and arrangement. Section 11.1 shows a study of the 22' (6.7 m) diameter module to determine its most efficient interior configuration.

Circulation patterns are very important to the efficient functioning of the human habitation areas. Circulation should be clear and uninterrupted to allow for easy travel from one place to another. Dual egress, which means to allow two means of exit from anywhere, should also be provided as a safety precaution.

Finally, the functional layout must be derived from functional adjacencies. In other words, the public areas should be isolated from the private areas, the work areas from the living areas. These separations allow for efficient use as well as psychological acceptance from the crew. Figure 11.0.1 shows further breakdowns of the public, private, work and living areas.

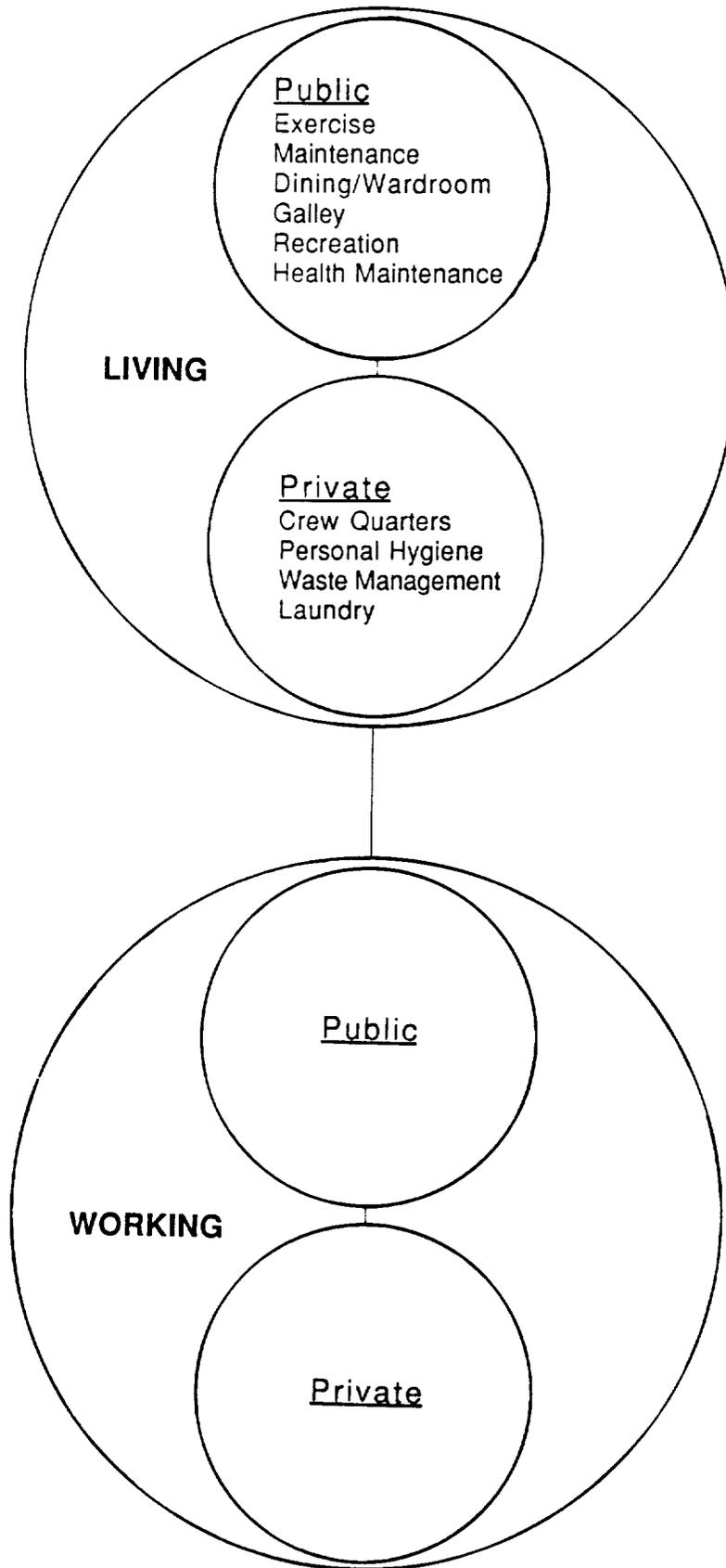


Figure 11.0.1 Functional Layout Breakdowns

The following section (11.1) is based on the conclusion that a two-level configuration is optimum for partial gravity applications. Section 11.1 is a study which investigates the various interior configurations that can be used with a two-level concept. Each configuration studied has diagrams and text to briefly explain the concept and pros and cons to show the good and bad points of each. The concept chosen is further explained in sections 11.2 and 11.3.

11.1 "Double-Node" Configuration

This is a two-level configuration with the circulation out of the module possible on either level. Dual egress is possible from anywhere in the module, which makes it only necessary to have one internal vertical circulation node (stairs, ladder, etc.).

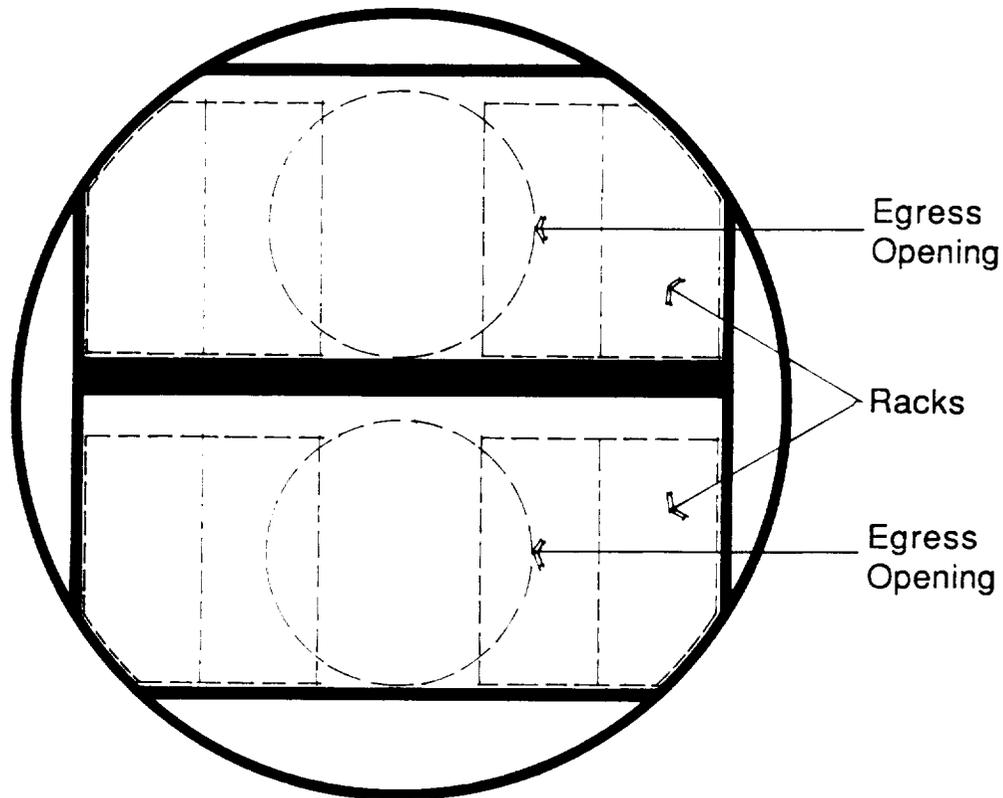


Figure 11.1.1 Cross Section

Pros

- Dual egress
- Space efficient

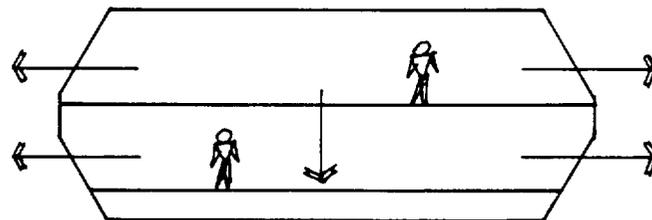


Figure 11.1.2 Long. Section

Cons

- Complicated endcones
- Requires complicated connecting nodes
- Heavy nodes

"Single-Node" Configuration

This is a two-level configuration with circulation out of the module possible at only one level. Dual egress is possible from anywhere in the module, provided there are two internal vertical circulation nodes at opposing ends.

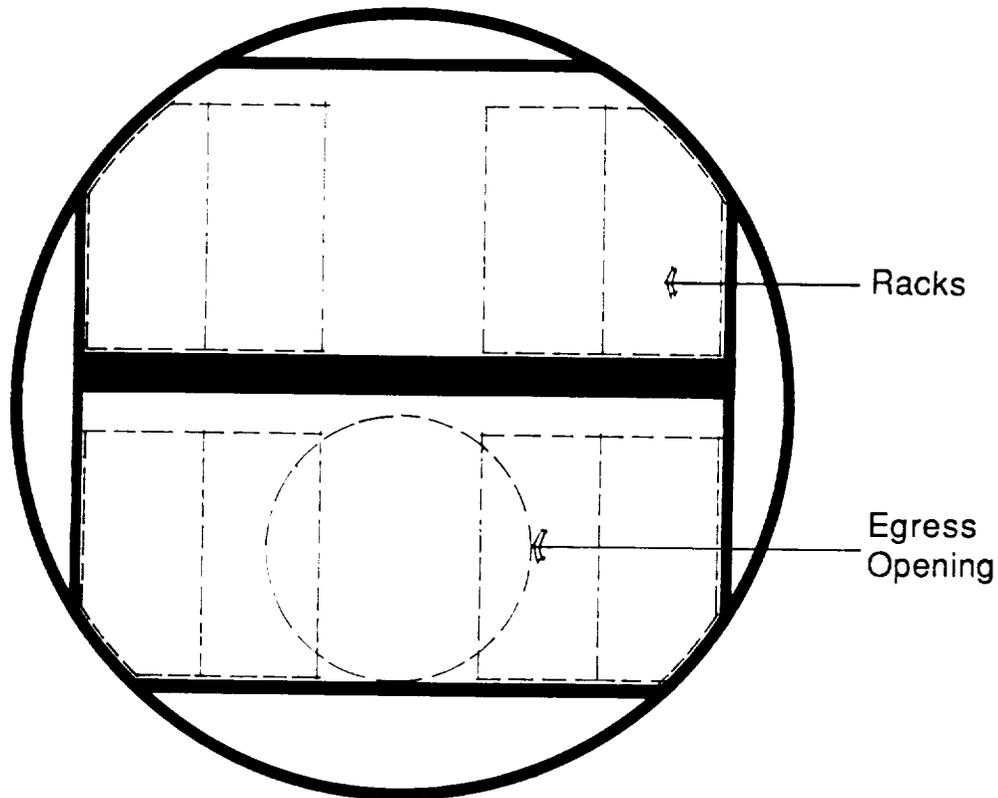


Figure 11.1.3 Cross Section

Pros

- Dual egress
- Simplified endcones
- Simplified nodes

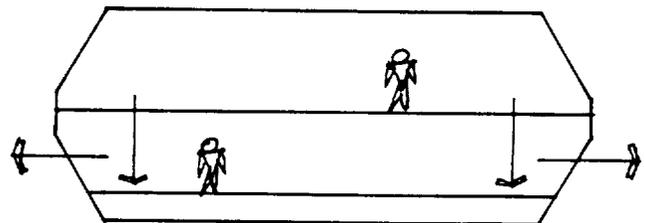


Figure 11.1.4 Long Section

Cons

- Space inefficient
- Inefficient circulation

"Isolated-Corridor" Configuration

This is a two-level configuration with circulation out of the module possible at an intermediate level, an isolated corridor. The isolated corridor could be pressurized and closed off in an emergency to provide an additional safety factor. Dual egress is possible from anywhere in the module, provided that vertical circulation to the intermediate level is provided at opposing ends.

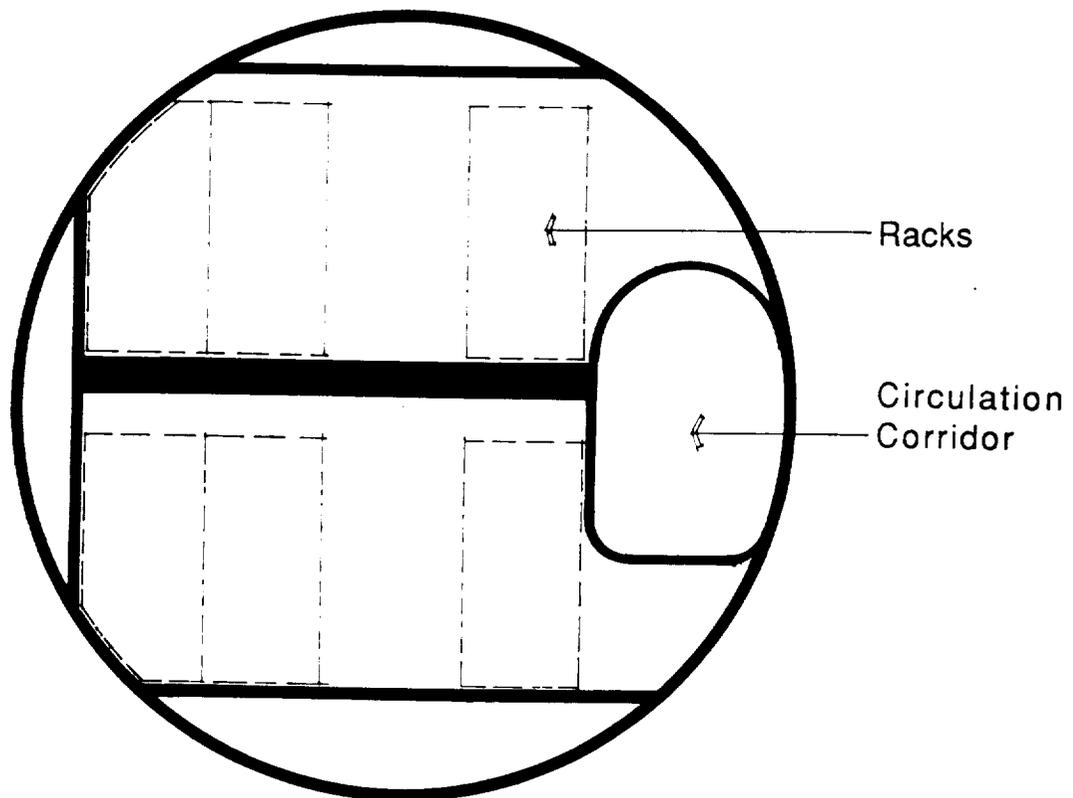


Figure 11.1.5 Cross Section

Pros

- Dual egress
- Safety factor
- Simulates Earth architecture

Cons

- Space inefficient
- Safety factor adds mass
- Complicated dual egress

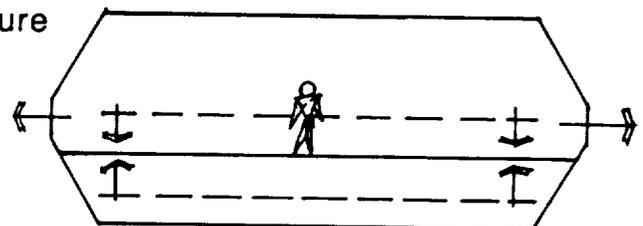


Figure 11.1.6 Long Section

"Double Isolated-Corridor" Configuration

This is a two-level configuration with circulation out of the module possible through isolated corridors at both levels. Dual egress is possible from anywhere in the module.

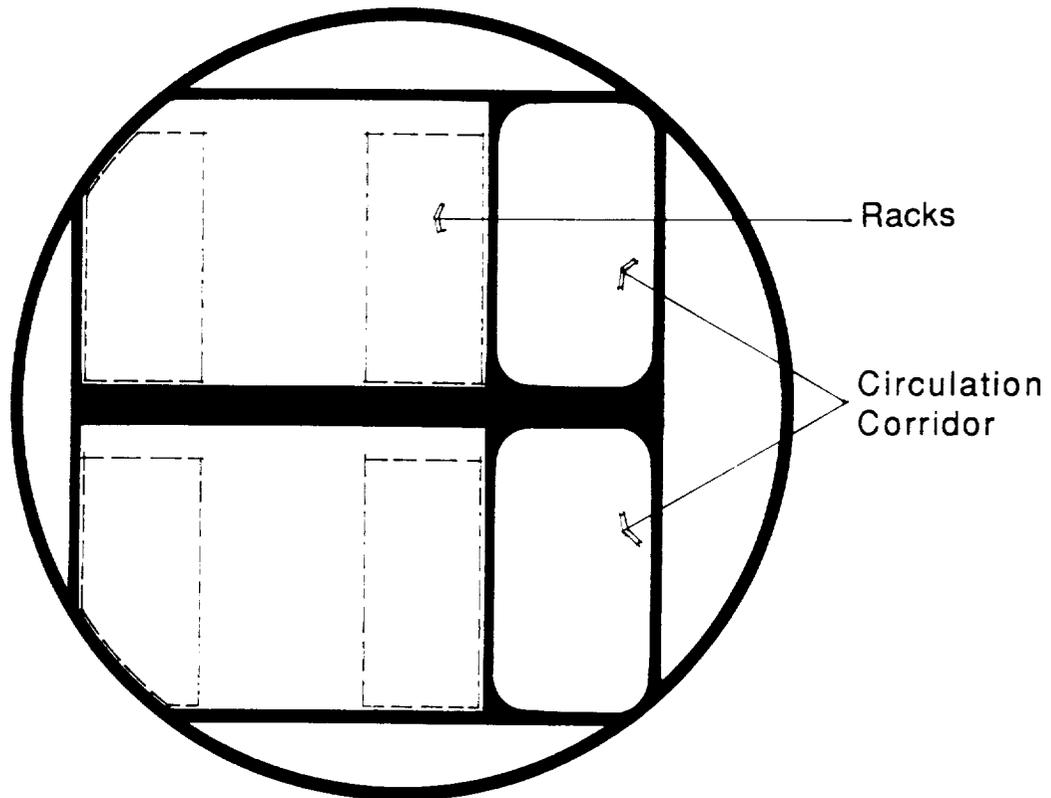


Figure 11.1.7 Cross Section

Pros

- Simulates Earth architecture
- Dual egress
- Safety factor

Cons

- Space inefficient
- Safety factor expensive
- Added weight
- Complicated end connections

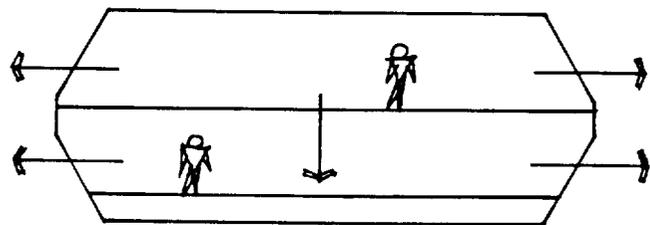


Figure 11.1.8 Long. Section

"Split-Level Egress" Configuration

This is a two-level configuration with circulation out of the module possible from either level by accessing an intermediate level at opposing ends. Dual egress is possible from anywhere in the module, and since vertical circulation is provided to the intermediate levels at the ends, no internal vertical circulation node is necessary.

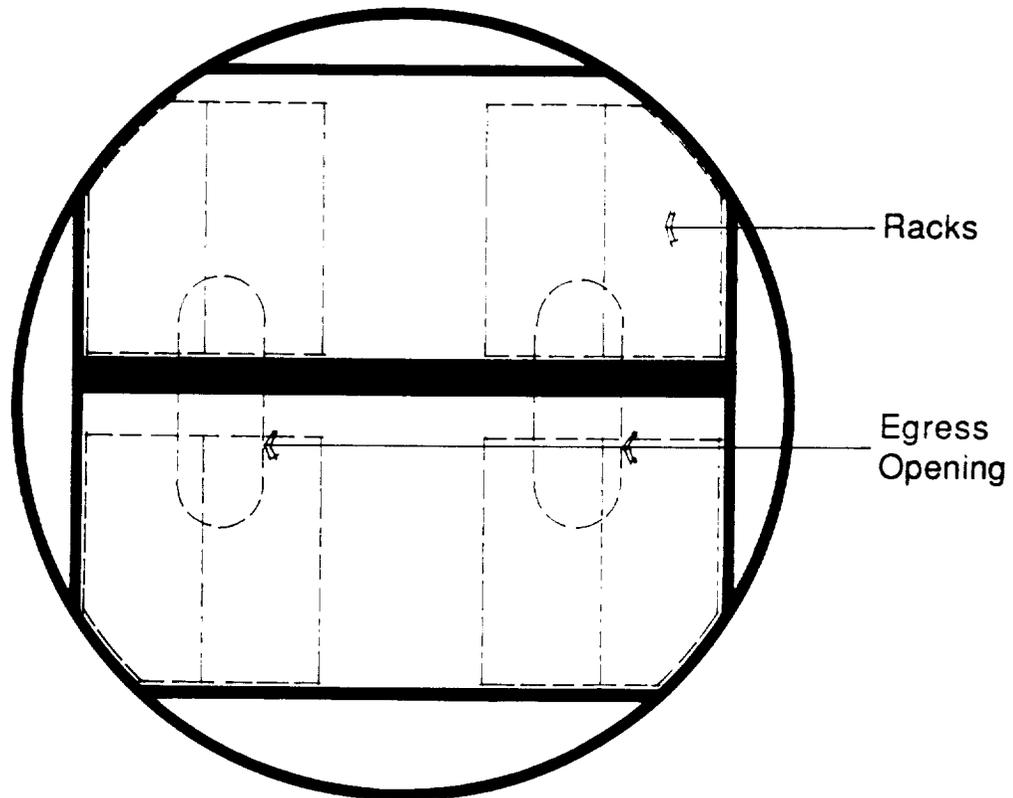


Figure 11.1.9 Cross Section

Pros

- Dual egress
- Space efficient
- Expandability
- Flexibility of interiors

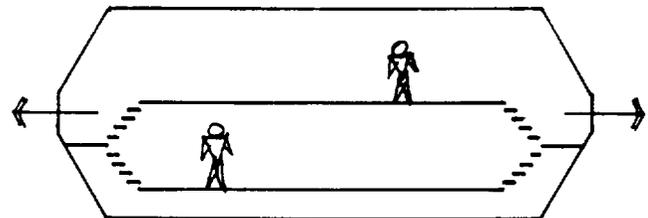


Figure 11.1.10 Long. Section

Cons

- Multiple openings in module

The "split-level egress" configuration is the sectional configuration that was concluded to be optimum. Therefore, this configuration was further studied and developed to arrive at the "optimum" partial gravity habitat for long duration spaceflight and settlement by humans.

11.2 Circulation

Circulation patterns are very important to interior architecture and should be studied and solved prior to beginning the functional layout. Dual egress has been established as an important safety factor and should be provided from anywhere within the module.

The "split-level egress" configuration (figure 11.1.9) provides the most space efficient and simple means of leaving the module in case of an emergency as well as providing a simple method of circulating from one level to the other. The dedicated circulation path, which allows two astronauts to pass while wearing spacesuits, is centralized, therefore dictating that the various functions be located off each side of the corridor.

The centralized circulation path is the most space efficient because it eliminates the need for secondary circulation. For instance, in the case of the "isolated corridor", the circulation path down the side of the module makes it necessary to provide secondary circulation and equipment access within each area, whereas, in the case of the "split-level egress", the centralized circulation path can begin to serve as both primary (dedicated) and secondary (equipment access, etc.) circulation.

11.3 Functional Layout

To begin the functional layout, the first decision was to separate the living areas from the work areas and the public areas from the private areas.

The living areas are separated from the work areas by placing them in different modules. In this manner, an Earth environment can be simulated by having the crew get up and travel out of their "home" to go to work and vice versa. It

should be noted here that the design of the work module is outside the scope of this project.

Since we are using a two-level interior configuration, the public living areas can be isolated from the private living areas by placing each function on one level. The private areas were placed on the lower level because, for planetary applications, it is the safest place in the event of a solar flare due to the added mass of material through which the particles have to travel. However, the two levels could easily be interchanged because of the modularity of the two-level concept. The upper level houses the public areas so that the ceiling height can be raised to give a more "spacious" feeling.

The lower level plan, which houses the private areas (figure 11.3.1), includes the following functions:

- Crew Quarters (12)
- Showers (3)
- Toilets (2)
- Laundry

The central corridor is 4.5' (1.37m) clear to allow for emergency egress and the ceiling height throughout is 8' (2.44m). The ECLSS is located under the floor and all of the plumbing fixtures are centralized to minimize excess piping runs. Finally, there is a cavity wall along the perimeter of the module to allow for mechanical runs and vertical chases (utility runs) at the four "corners" to carry air ducts to the upper level.

The upper level plan, which houses the public areas (figure 11.3.2), includes the following functions (see section 8.0 for area breakdowns):

- Exercise
- Maintenance
- Dining/Wardroom
- Galley
- Toilet
- Recreation
- Health Maintenance

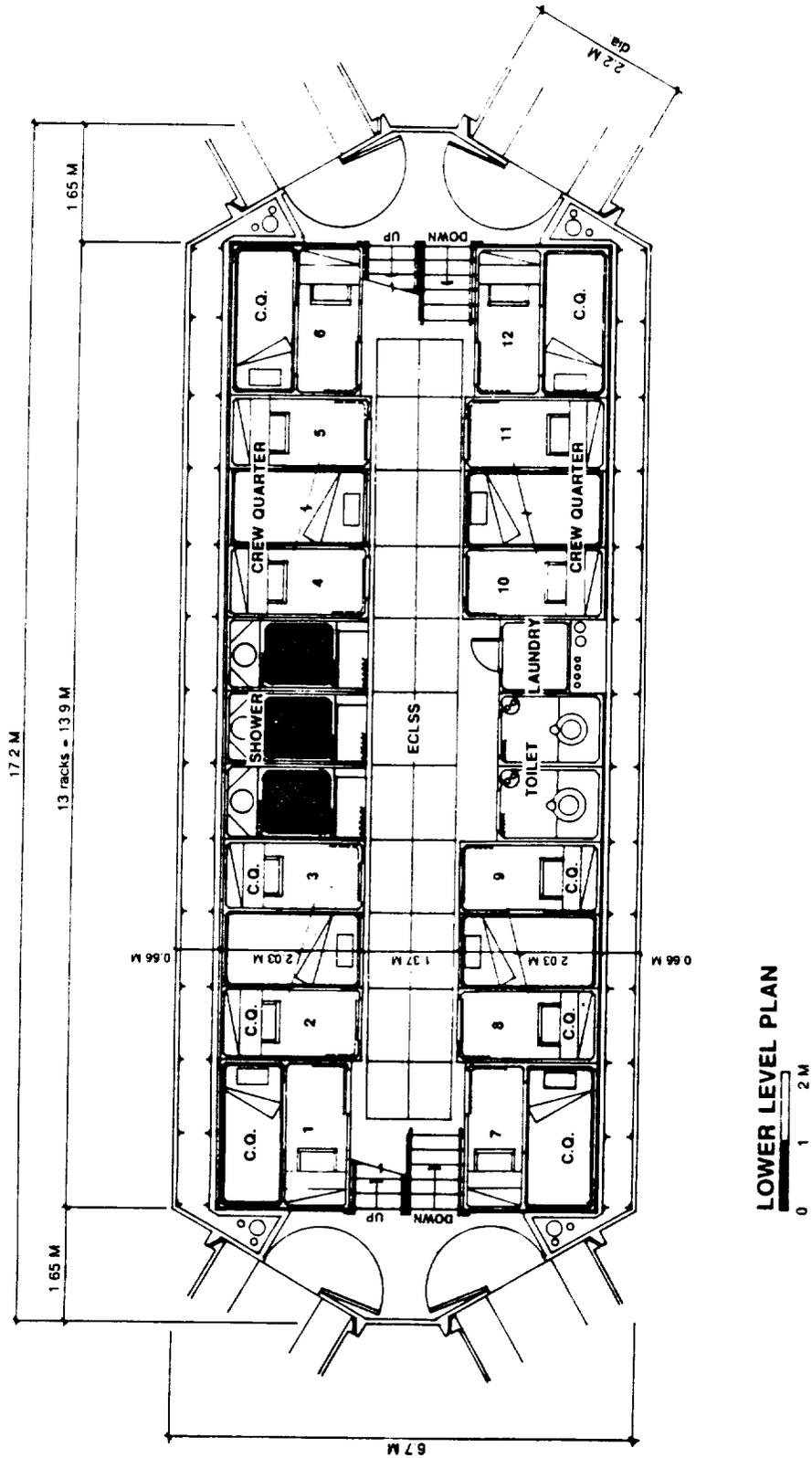


Figure 11.3.1

The exercise area includes an exercise bench, a treadmill and a bicycle so the crew can maintain healthy bodies (section 8.0). The maintenance area is dedicated to periodic repair of facilities. The dining/wardroom can accommodate the entire crew of twelve (12) and has a projector and screen for meetings. The galley has storage areas for food as well as preparation facilities for the entire crew. One (1) toilet facility has been provided on this level and is grouped with the galley water supply to minimize the plumbing piping from the ECLSS. The recreation area can accommodate seven (7) crew members and can be used for conversation, music listening, reading or visual entertainment (movies, etc.). The recreation area can be closed off by curtains to give privacy. The dining table can be used for cards and games as part of the recreation area. The health maintenance facility is located near the exercise area for monitoring of the crew and has a fold-up bed for the care of the crew when injuries occur.

Figure 11.3.3 is a longitudinal section through the habitat module that illustrates how the circulation and ECLSS work. Circulation from both levels is connected to an intermediate level at opposing ends of the module from which the crew can exit. The ECLSS is located under the floor from where it distributes air up the vertical chases to each level.

Figure 11.3.4 is a cross section through the habitat module that shows the structure and the mechanical spaces. The floor structure is made up of aluminum trusses with perforations to allow air ducts and electrical conduit to pass. The cavity walls and the upper ceiling show how ducts and conduit are distributed to supply air and power.

Figure 11.3.5 is an isometric of one personal crew quarters. Each crew member will have his own private area with a desk, shelves and personal storage. Crew sleeping is accommodated in a "bunk" type configuration, as shown in figure 11.3.6. Although the beds are stacked, each crew member has his own private sleeping area and entrance to the sleeping area.

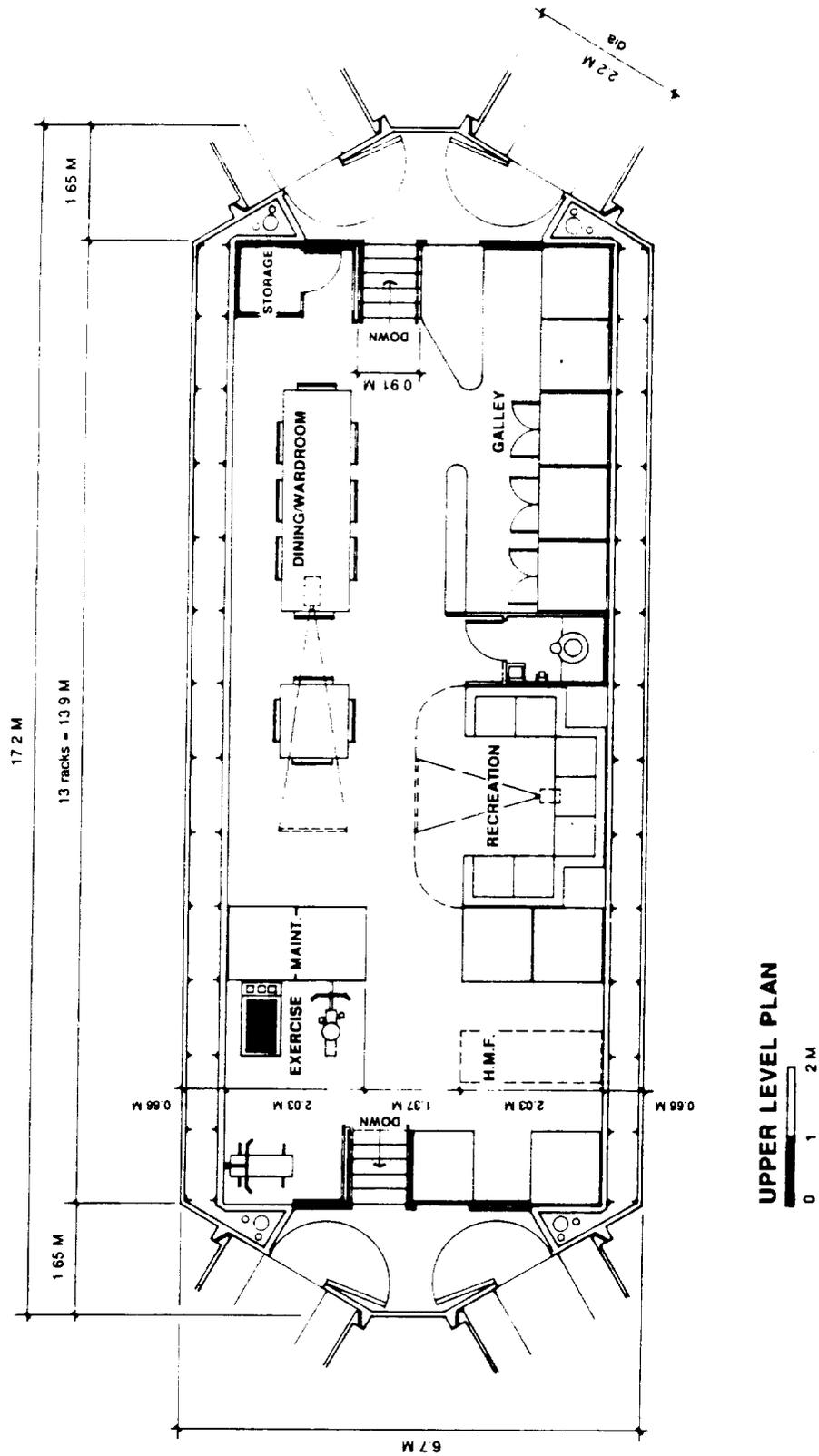


Figure 11.3.2

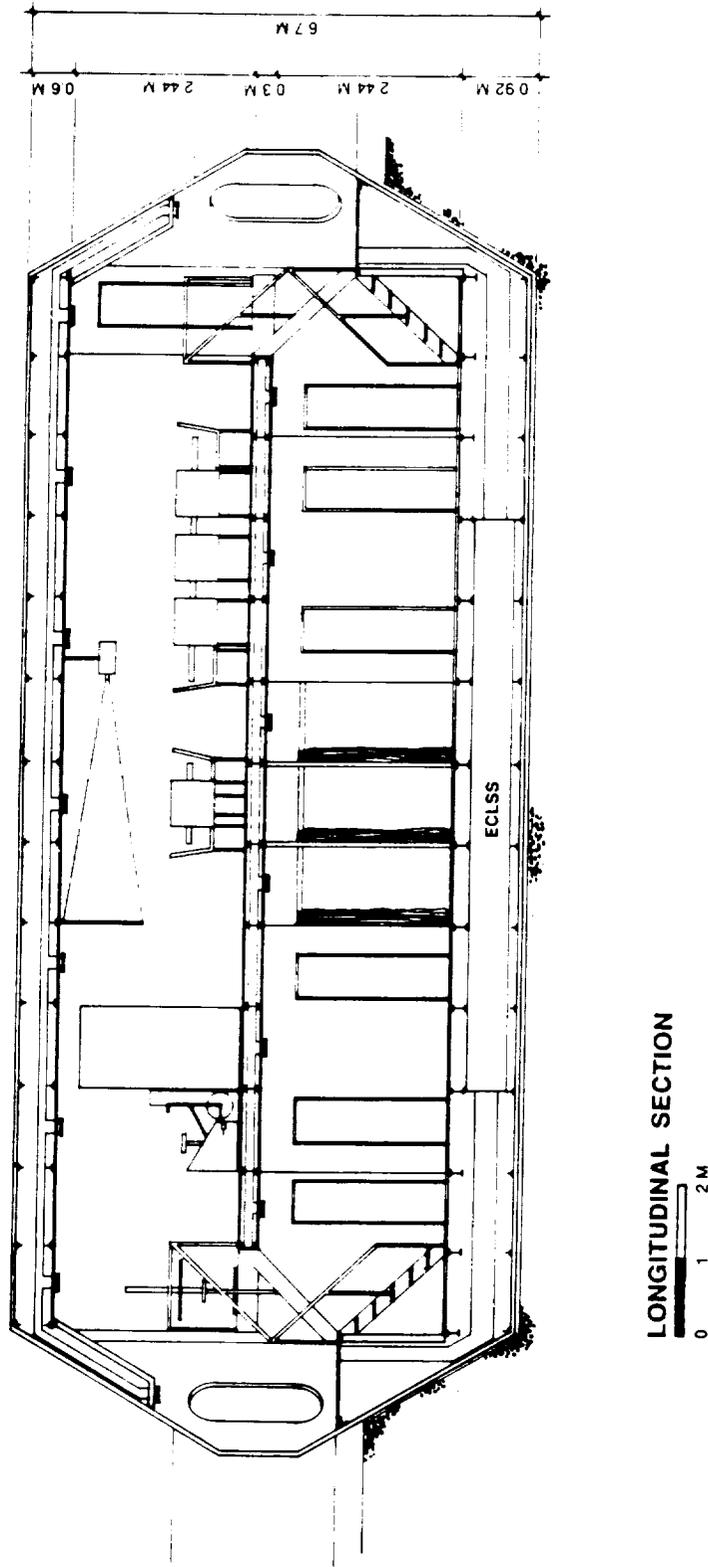
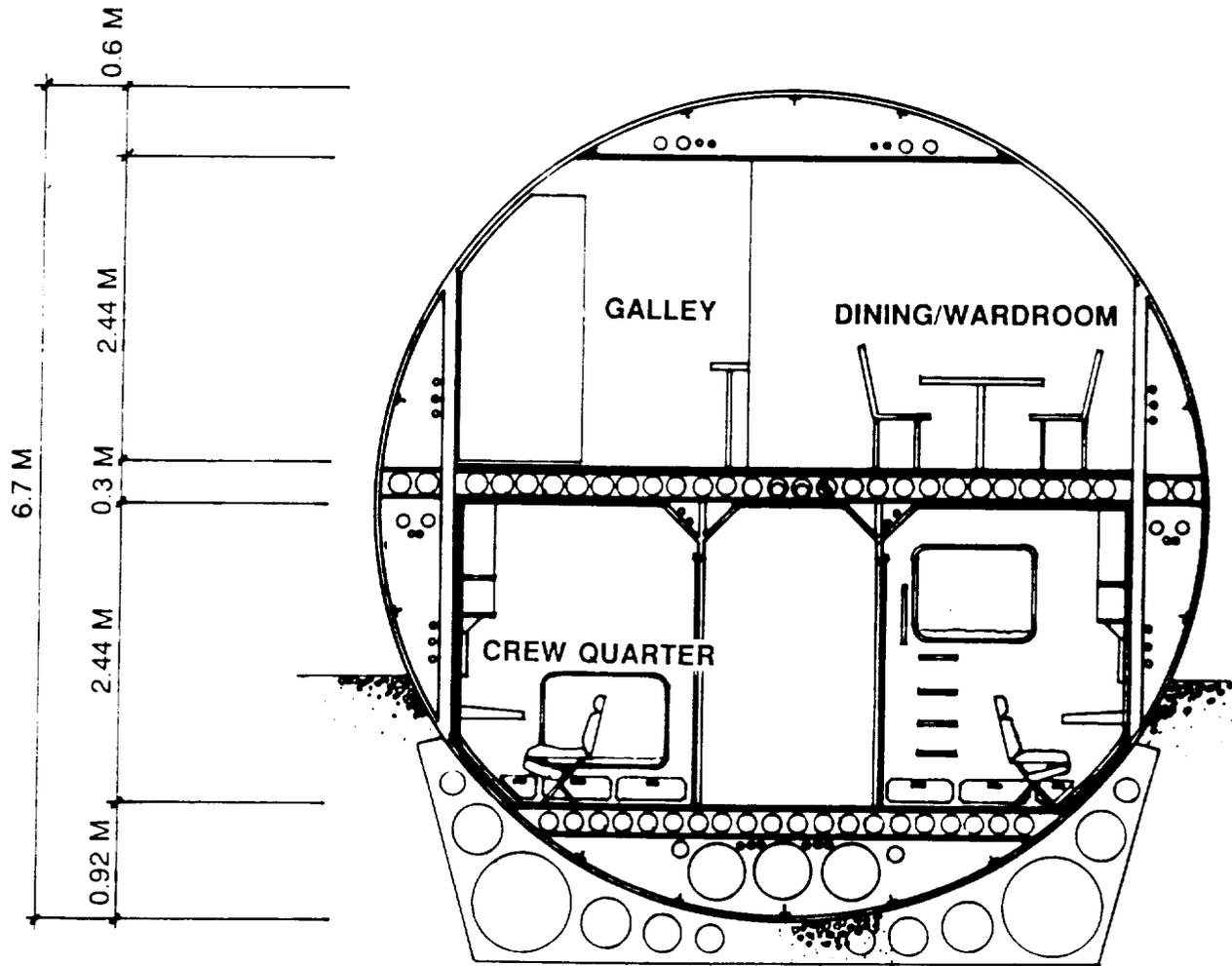


Figure 11.3.3



CROSS SECTION

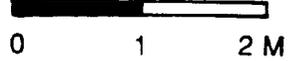
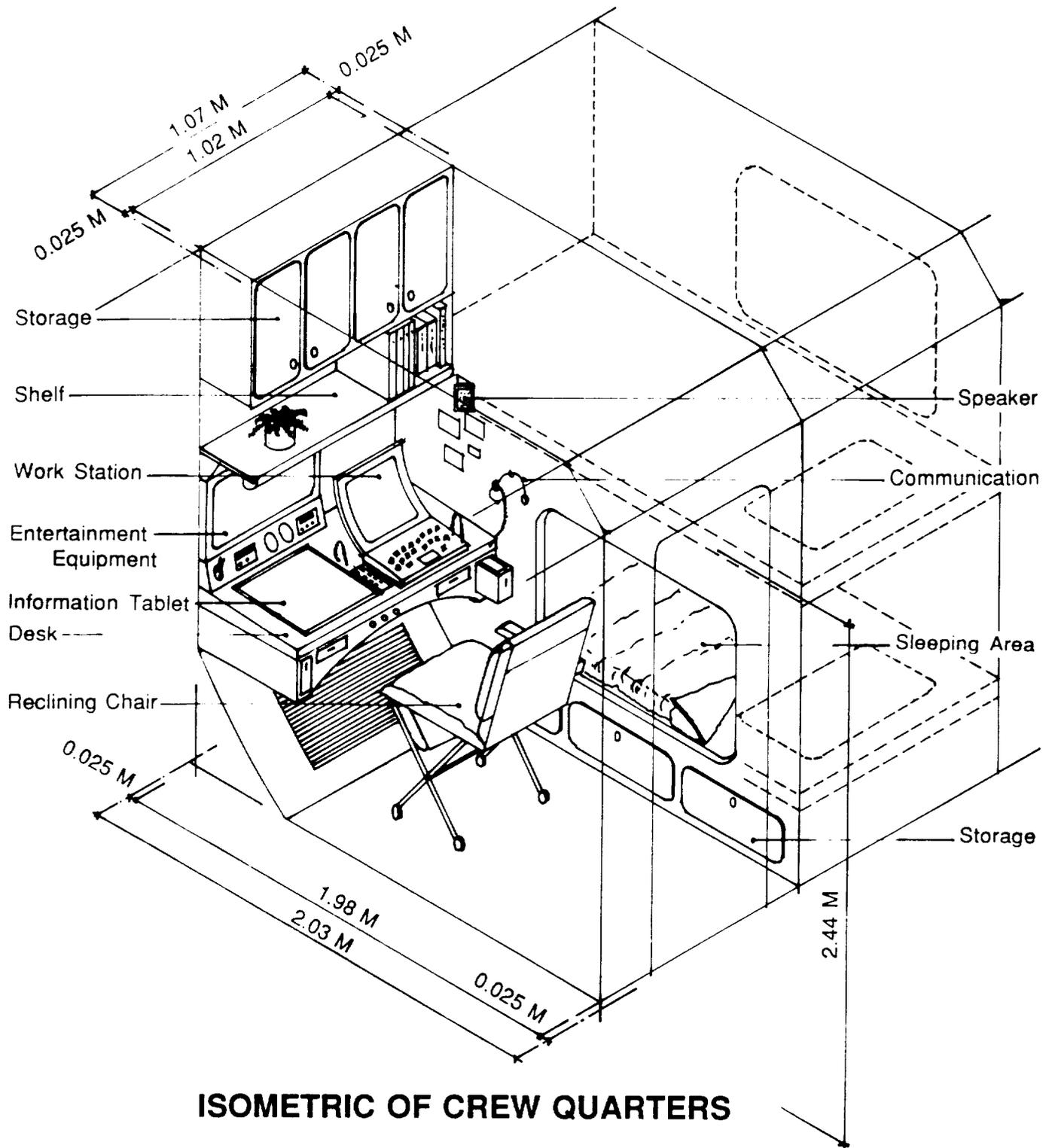
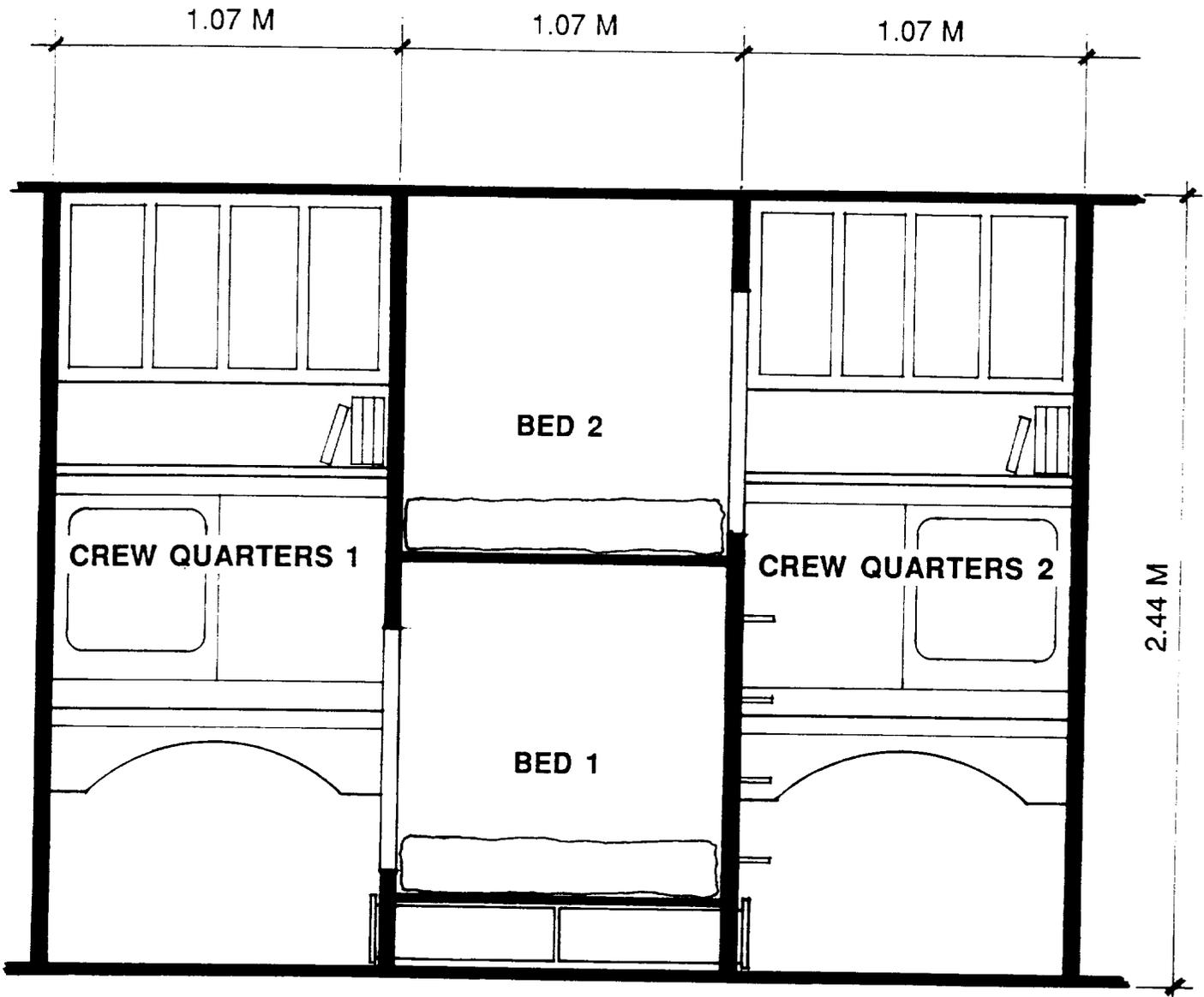


Figure 11.3.4



ISOMETRIC OF CREW QUARTERS

Figure 11.3.5



SECTION OF CREW QUARTERS

Figure 11.3.6

In conclusion, this functional layout satisfies all the previous requirements set forth by the partial gravity design requirements. Therefore, this design can now be taken from the micro-interior scale to the macro-scale in application to a Lunar Base.

12.0 Exterior Architecture

12.0 Introduction

While the interior architecture was being designed, the exterior architecture and configurations were also being designed. It was necessary to determine the most practical, functional, and safe configuration.

For practicality, the configuration must lend itself well to growth and expansion as well as ease of installation and construction.

The modules must be functional in configuration due to the harsh and extreme conditions of the Moon. Being that the initial base is to house roughly 36 crew members, and is to be built primarily from Earth launched goods, it was necessary to save weight wherever possible without hindering the functionality of the base. This means that the design must be very flexible within its own restraints to provide optimum functionality.

The safety factor of the base configuration is also a very important issue. This is mainly because of the isolation and distance from Earth and also the harsh conditions of the lunar surface. Because of this, dual egress became an issue of concern. Dual egress means that there is always a safe area to escape to in the event of an emergency, and that no "dead ends" are created as a result of the layout. This issue was stressed in meetings we had with Colonel Gerald Carr, commander of the third Skylab mission.

12.1 Module Configuration

The most important issues in the module configuration study were dual egress, phased growth, and modularity. To determine what type of configuration would best suit our purposes, studies of four basic geometric forms were made. Geometric forms were studied because the modules to be used are all uniform, therefore geometric growth is preferred.

Dual egress was considered to be one of the most important safety issues to address in the design of the lunar base. There should also be complete circulation throughout the base even in the event of a module being damaged and unusable.

Phased growth is an important aspect of construction regardless of the location because it optimizes time, materials, effort, and most importantly, money. On the Moon however, there is the added element of being remote and separated from Earth, and having a harsh and extreme environment. There is also the fact that all of the materials and supplies to be used on the initial base are Earth launched and arrive at different times. This means that construction methods employed must allow for phased growth yet at the same time must be self-contained between phases.

It is important that the base be made of limited numbers of different modules which are used as standard parts throughout the base. By having continuity in modules, the base becomes more economical in that no time is spent making allowances for special or out of the ordinary pieces. Also no time and money is spent providing special systems to accommodate one-of-a-kind modules or amenities.

Two dimensional configurations were the only ones studied because it was found that in trying to erect, stabilize and support vertical configurations, it became difficult, time consuming and expensive requiring much additional structure, and extensive EVA (ExtraVehicular Activity) time to achieve the task.

The cost factor was a very important issue to consider while designing the lunar base. Being that all of the supplies and materials for the base are to be launched from Earth, it is important to consider the cost per pound of payload. Due to the tremendous masses that must be launched, weight was reduced wherever possible.

Hard nodes are the main source of access-egress for all pressurized facilities and also serve as storage areas for EVA suits. Hard nodes are relatively heavy and therefore expensive to transport to the Moon from Earth. The use of hard nodes became limited as our design developed as will be seen later.

The following are studies of four different potential configurations. The configurations are based on geometric forms utilizing modules of equal size to keep the geometry simple and basic. Each study is then evaluated via pros and cons to determine which is the most practical to be used as the lunar base configuration.

The studies were limited to simple geometries to reduce any difficulties that may be incurred during construction of the lunar base. The more complex the design, the more difficult it is to initiate. Things are also kept as simple as possible due to the serious and hard conditions of the lunar surface.

Triangular Configuration

The triangular configuration meets requirements for the lunar base such as dual egress, uniform growth of the configuration, and it lends itself well to planetary application having many points of ingress/egress on the perimeter. However, as a result, the distance to the hard nodes is increased because of the angle at which the modules meet, nodes become complex requiring six openings instead of four, and it would be difficult to incorporate an overhead structural system for radiation or thermal protection should the need arise.

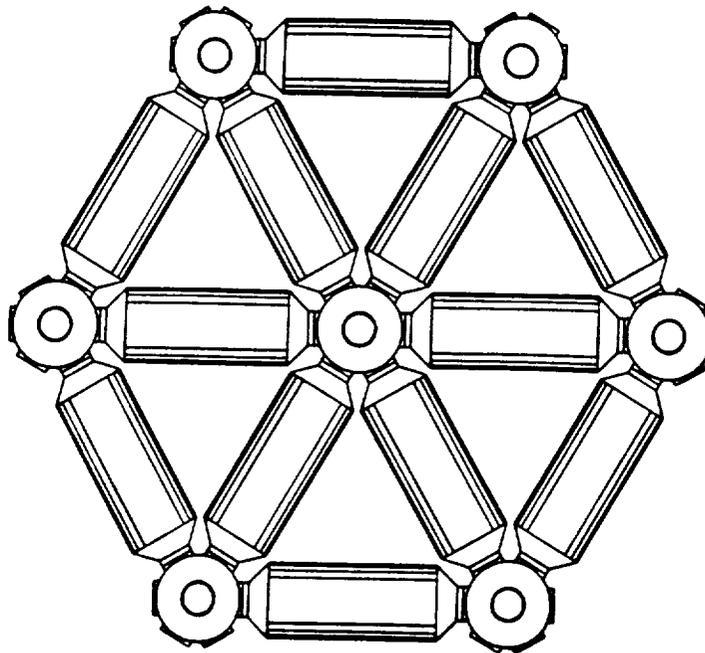


Figure 12.1.1 Triangular configuration

Pros

- Dual egress
- Uniform growth
- Good for planetary application

Cons

- Extended distance to nodes
- Nodes become complex
- Difficult to incorporate structure

Raft Configuration

We found that the raft configuration met only one of the requirements for the lunar base, this being dual egress. To achieve dual egress however, it would require many hard nodes (which are very heavy and therefore expensive), and the growth of the configuration is limited to a single axis.

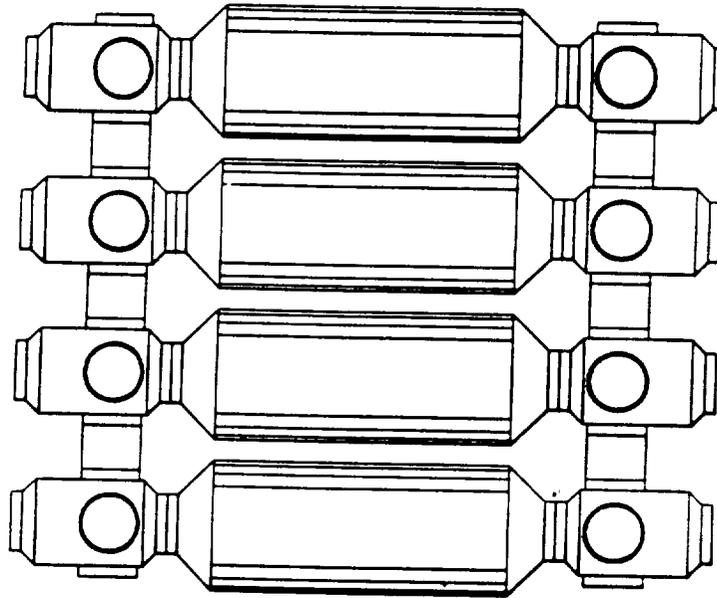


Figure 12.1.2 Raft configuration

Pros

- Dual egress

Cons

- Requires many nodes
- Limited growth

Linear Configuration

The linear configuration requires the least amount of nodes (only two). As a result of this, there is no dual internal egress (i.e. if you were standing at the end of an end module, and an explosion occurred, you would only be able to exit via an airlock, vs. to another module). Circulation is limited to linear, and the growth is limited to linear.

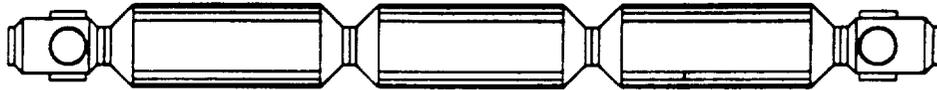


Figure 12.1.3 Linear configuration

Pros

- Limited number of nodes needed

Cons

- No dual egress
- Limited circulation
- Limited growth

Grid Base Configuration

By using the grid base configuration, dual egress is provided, growth of the base is uniform and omnidirectional, the configuration lends itself well to planetary application, a structural grid system can be easily incorporated if needed, and the hard nodes used are standard space station nodes. However, four modules are needed to complete each configuration.

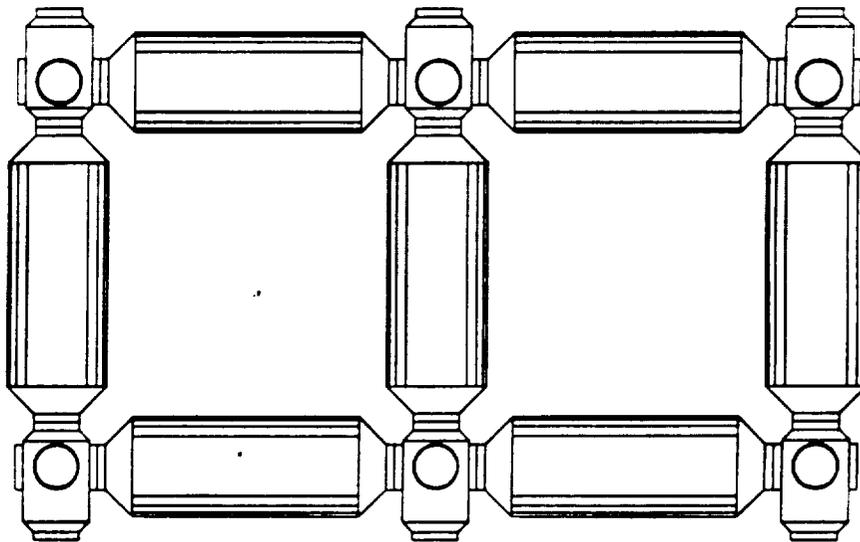


Figure 12.1.4 Grid base configuration

Pros

- Dual egress
- Uniform growth
- Good for planetary application
- Structure is easily implemented
- Nodes are standard

Cons

- Four needed to complete configuration

As a result of the configuration study, the grid base configuration was chosen for the base. It was chosen based primarily on the pros discussed on the previous page.

When first conceptualized, the configuration was slightly different. One out of each group of four modules was to be buried, with the other three sitting on the surface of the Moon. This configuration allowed for uniform growth yet at the same time allowed for vehicular access to all areas of the base regardless of the number of modules. Figure 12.1.5 shows the possible configuration, the dashed modules being the buried ones.

By having one module in each group buried, this allowed for covered areas for vehicle storage and protected EVA. This goes to say that assuming a radiation protection device is employed, there could be a network of covered/protected areas between the modules.

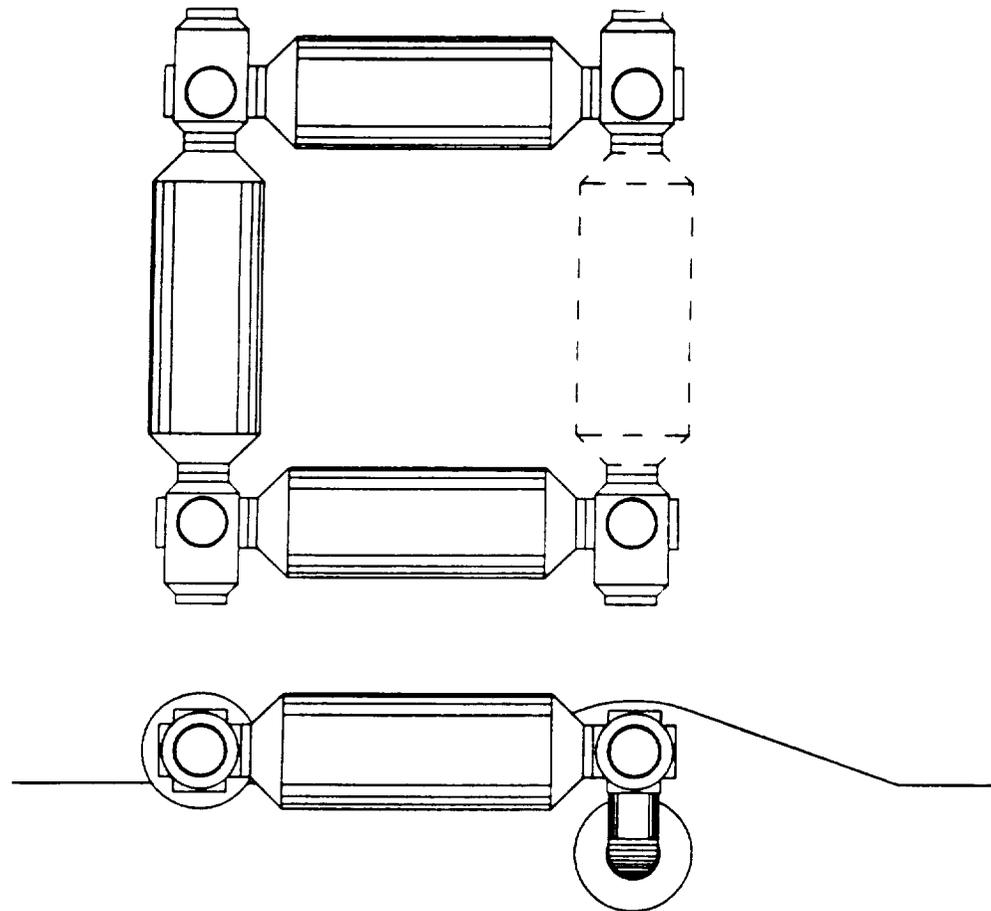


Figure 12.1.5 Preliminary Configuration.

After careful review of this system, it was decided that this system did not meet our requirements completely. Having a specific covered area for EVA and vehicle storage was abandoned after numerous conversations with Dr. Alan Binder of Lockheed. It was pointed out that there would be no activities of scientific importance which would be performed in the covered area. It was also determined amongst the group that there would be a dedicated facility for vehicle storage and maintenance, so the covered outside area lost its validity. In addition, the covered area proved too small to serve any identifiable purpose, and the additional cost of covering the area was deemed too expensive.

The configuration as it now stands consists of the grid base configuration with all modules on the same plane. There is a group of four modules accompanied with two flanking groups of three. A compromise was made on the dual egress in the base configuration, the two open ended modules are capped off with airlocks to provide a save area to escape to in the event of emergency. The open areas are provided for future expansion, see below.

It is imagined that for future growth of the base and the addition of crew members, the new facilities would be made from cast basalt or some other lunar derived materials, to relieve the high cost of Earth delivered goods. In the event that the use of lunar materials is unsuccessful, similar modules would be placed in the voids which are present.

Figure 12.1.6 is an illustration of the base in its final configuration for a crew of 36. The group of four modules consists of three (3) habitat modules and one work module, while the flanking groups of three (3), are composed of work and laboratory modules.

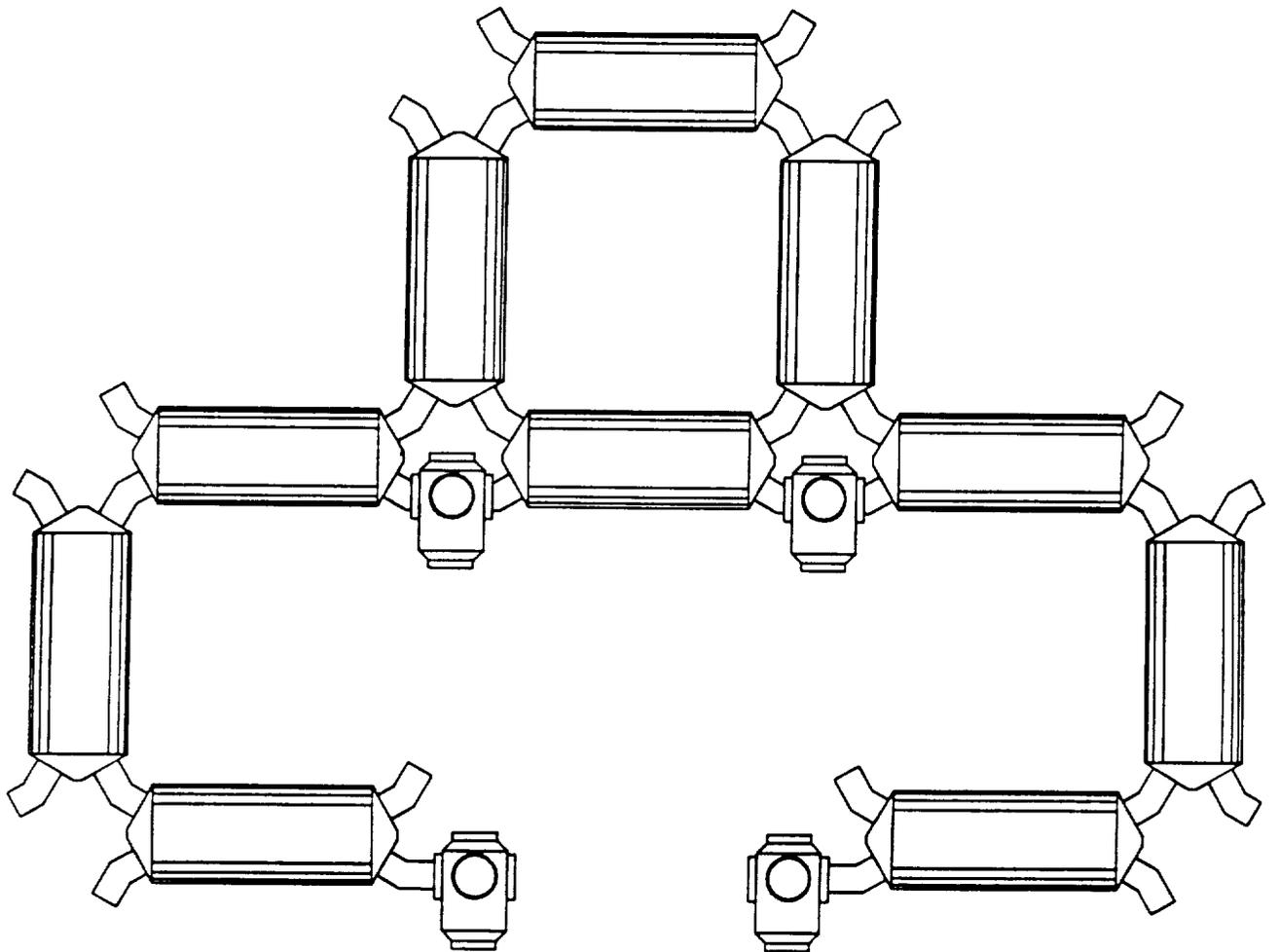


Figure 12.1.6 Base Configuration.

12.2 Phasing

The most efficient method of construction for a large facility such as the lunar base, is to have phased construction. In the configuration and scale we have determined, the lunar base will be constructed of Earth launched goods. These materials and supplies will be arriving at different times as outlined in the scenario (see appendix A).

The first module to be landed will be a work module which can sustain a crew of four for a year. The following three modules will be habitat modules, each of which can sustain a crew of twelve for an indefinite period of time. For detailed plans and sections of these modules, please refer to figures 11.3.1-6. The remaining modules will be dedicated to work stations, laboratories, storage of perishables and non-perishables, and recreational facilities.

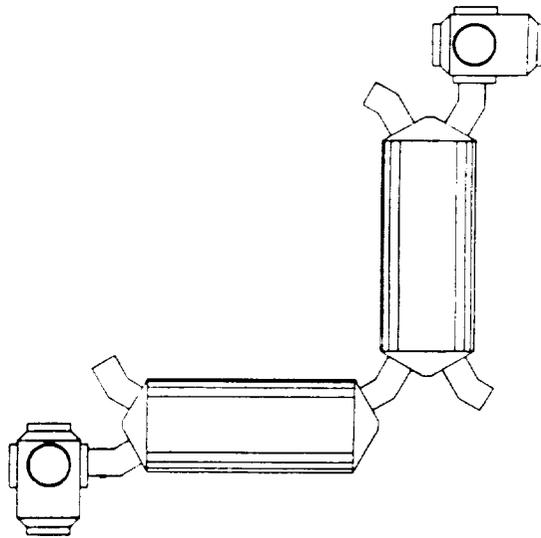
The first module landed will be placed with its long axis oriented east-west. It is oriented in this manner due to the overall configuration of the base being oriented on a north-south axis (see figure 14.1.2). The first module landed is the southern most module in the group of four to be covered with regolith (see figure 13.3.2).

The second module will be the first of the habitat modules and will be placed with its long axis orientated north-south, as shown in figure 12.2.1 a. This can happen on either side of the first module (east or west), but it must be oriented north-south in order to connect with the first module. The third through tenth modules are added as indicated in figures 12.2.1 b - e.

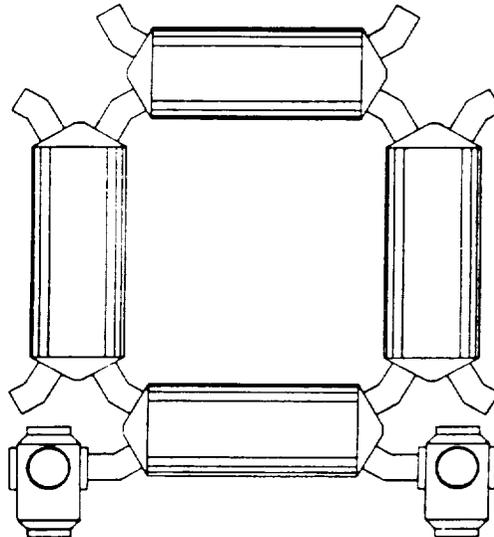
All necessary auxiliary components of the base will be waiting near the construction site, having been left by the earlier unmanned missions between 1998 and 2004.



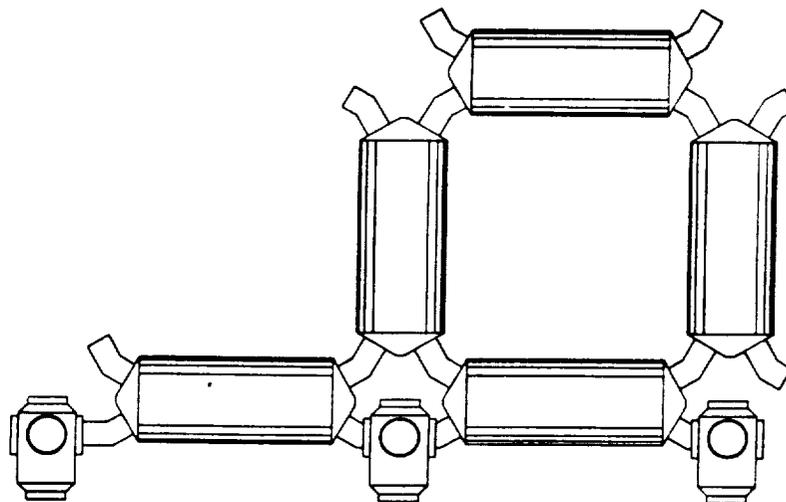
A.



B.



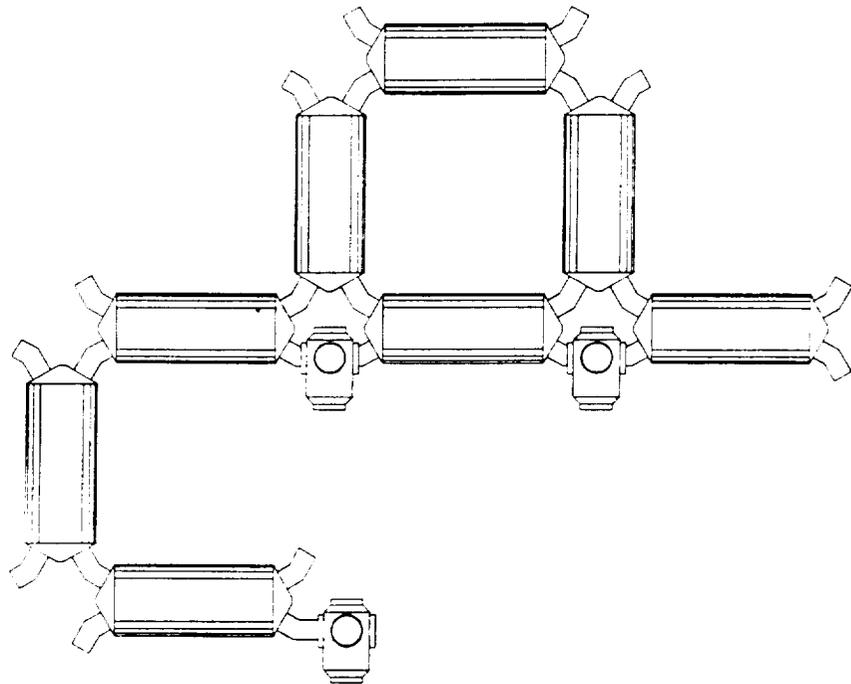
C.



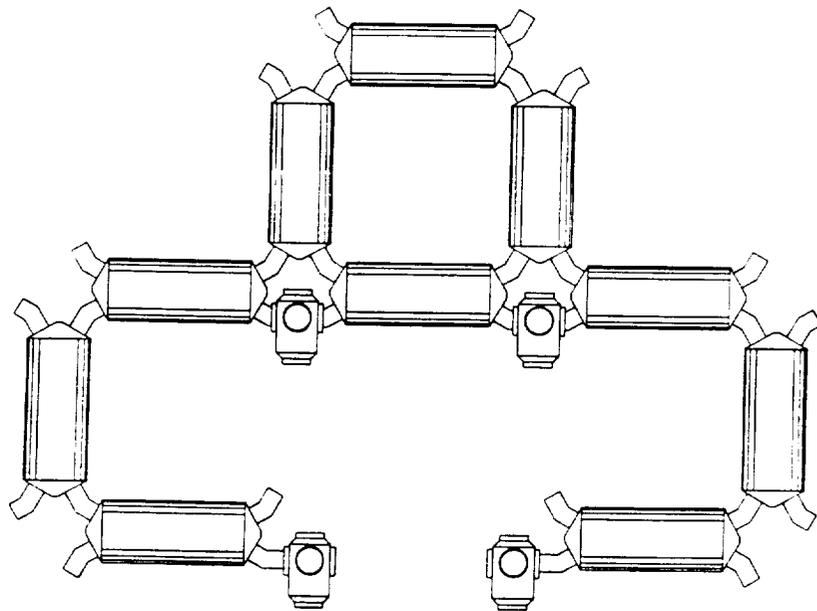
Figures 12.2.1 A-B Phased growth



D.



E
Figures 12.2.1 C-E Phased growth



Issues beyond the scope of this project are, how is the site prepared for reception of the modules, how are the modules moved into position from the landing site, and how is the dust controlled during movement?

An assumption was made that the mining and regolith moving equipment which will be there for the LLOX processing plant, will be used for preparation of the lunar base site. It is possible that the dust can be controlled with a sintering process.

For the movement of the modules from the landing site to the base site, it is assumed that there will be a vehicle which is capable of this exercise. A multi-purpose lander/trailer as presented in the USRA report A Manned Lunar Outpost June 1988. The vehicle will connect at one end of the module with the structural support ring, where the adjustable footings are located. On the opposite end of the module at the same location, a wheeled pallet will be attached (see figure 12.2.2).

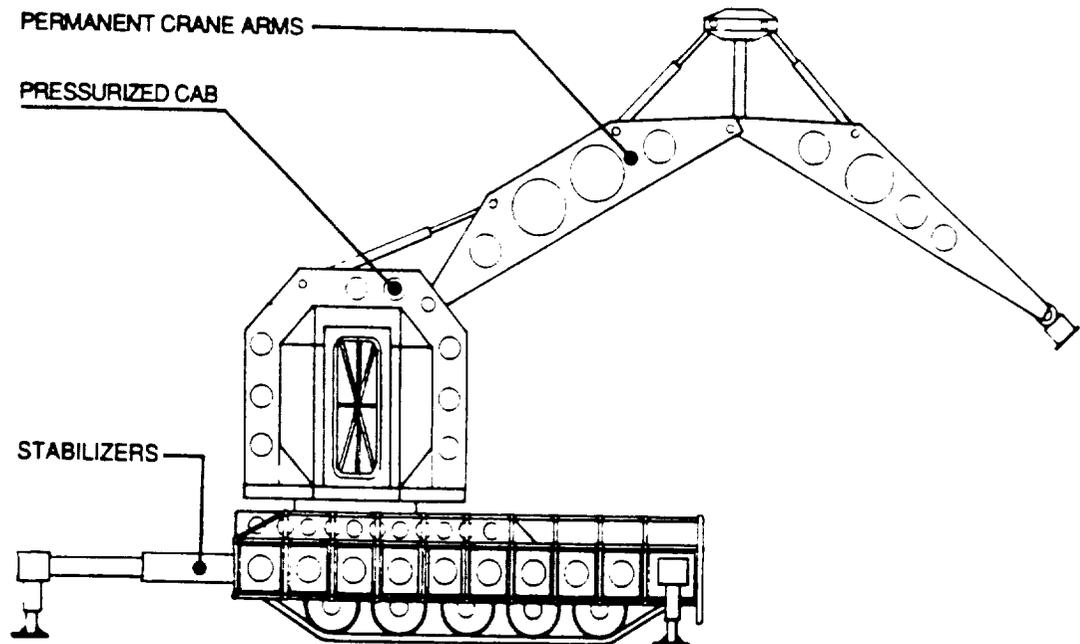


Figure 12.2.2 Transportation vehicle

By having phased construction it is possible to build the base in an orderly manner, providing optimum safety while limiting the amount of time wasted during construction and implementation.

12.3 Connection Nodes

A large amount of the expense incurred in establishing a facility such as the lunar base, is the extreme cost of sending supplies and goods to the lunar surface from Earth. The more an item weighs, the more expensive it is to get that item to its final destination.

Being that everything for the initial base is Earth launched, it is important to reduce the mass wherever possible. In section 12.1, different configuration studies were made. Many of the configurations studied required a large number of hard nodes or airlocks. Figure 12.3.1 shows a typical hard node as planned for Space Station Freedom. These hard nodes are extremely heavy, and the more that can be eliminated, the more cost efficient the project becomes. These hard nodes are heavy due to the reinforcement material required around each penetration. The more penetrations on a hard node, the more reinforcement material required, and thus the heavier the hard node becomes.

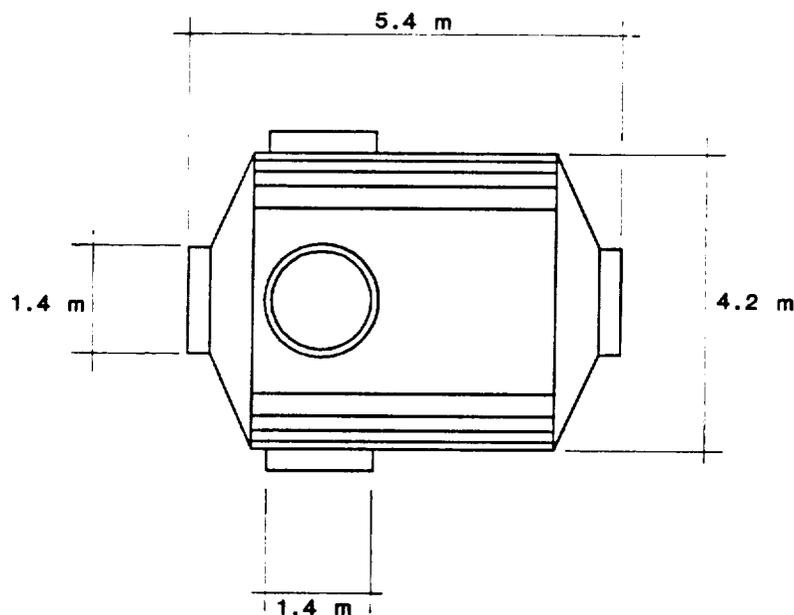


Figure 12.3.1 Hard node (McDonnell Douglas)

Through the design of the interior of the modules, our team found that a different means of ingress/egress was needed. With this determined, the connections between modules was then studied. It was found that many nodes could be eliminated if a flexible tube-like connector could be substituted.

Some time was spent looking for a flexible connector to take the place of the hard nodes. The specific connector we were looking for was not found, so we took the technology of an existing flexible connector and applied it to our own design. Figure 12.3.2 and 12.3.3 show the flexible connector planned for application in the lunar base.

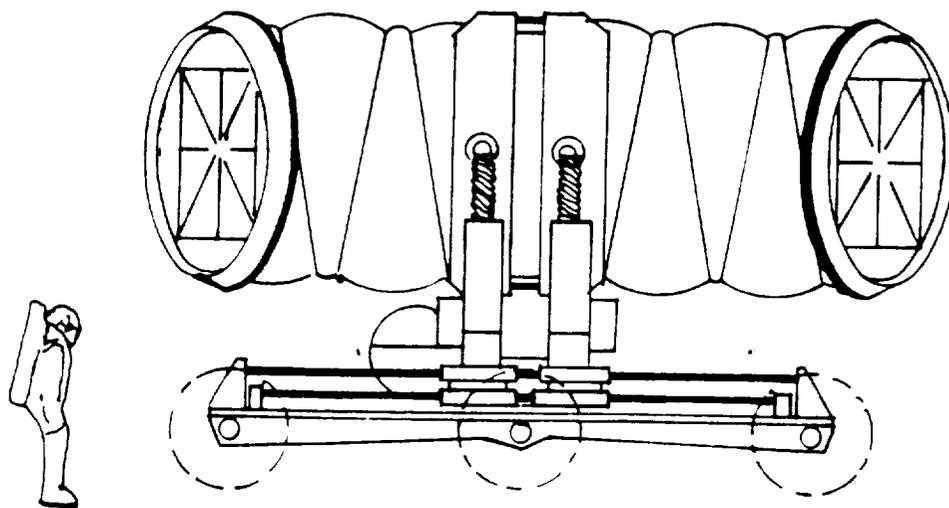


Figure 12.3.2 Flexible connector elevation

The flexible connector shown here was adapted from the Lockheed Planetary Surface System Elements Catalog.

The connector would have three modes of adjustment. There are four electric motor jacks which are used for vertical adjustments and compensation of height differences. The whole connector can be moved in any direction with the mobile platform it rests on, and there is also an adjustable collar built into the connector to allow for adjustments and corrections laterally in the connector.

By using the flexible connectors instead of the hard nodes, there will be a tremendous savings in the amount of mass which has to pass through LEO (Low Earth Orbit). They will provide a functional hard link between modules, and they are flexible enough to compensate for small differences in heights and distances between modules.

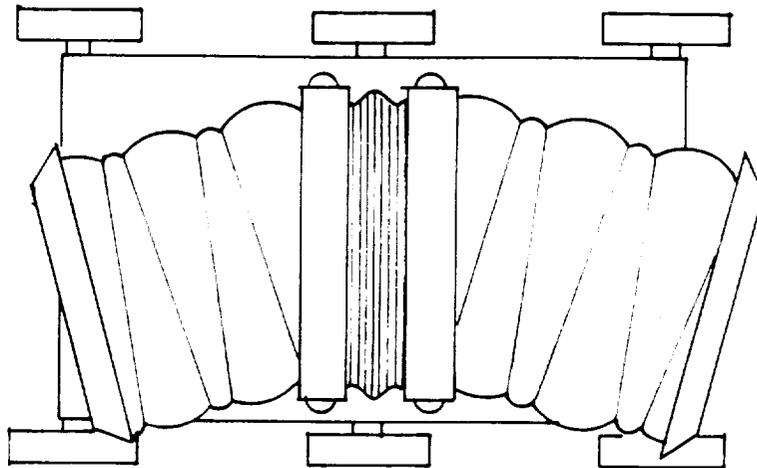


Figure 12.3.3 Flexible connector plan

13.0 Radiation Protection

13.0 Introduction

The major concerns while designing the lunar base, were the harsh and extreme conditions which are present on the Moon. Temperature, atmosphere, radiation, and surface constraints are the issues of most importance, with radiation issues having the most serious effects.

Unlike the Earth, the Moon has no atmosphere or magnetic fields to protect it in any way from the harmful or deadly doses of this radiation which bombard it almost constantly. Radiation shielding on the Moon could be achieved by placing a predetermined amount of mass between the radiation source and the crew living inside the base. Since mass is the key issue in radiation shielding, it would make sense to use in situ materials wherever possible, and save the great expense of bringing thousands of metric tones of material from the Earth's surface.

The next question is, how much mass is required between the radiation source and the inhabitants of the base? Since there are two types of radiation hazard which are experienced, there can also be variations in the level of radiation shielding provided. There can be protection which provides for only the background GCR's (Galactic Cosmic Radiation), and also protection for solar flare events. Solar flare events being more hazardous than GCR's and therefore requiring more protection.

The following is the study performed to determine the amount of radiation protection required and also the method by which this is achieved.

13.1 Initial Protection

The use of in situ materials for radiation shielding would be in the form of lunar regolith. The regolith can either be used in its raw state or as a by-product from some industrial process, since the Lunar Base would be

performing some sort of industrial activities. According to Silberberg et al. (1985), permanent dweller on the Moon can spend roughly 20 percent of their time without any significant shielding, providing they spend the rest of their time under at least 400 g/cm² of shielding. This amount protects the inhabitants from the cosmic radiation, but to protect for gigantic solar flare events, a shield of at least 700 g/cm² is necessary.

How the masses stated above translate into actual depth or thickness of regolith depends on the density of the regolith used. The bulk density of the lunar surface regolith varies from .9-1.1 g/cm³ from 0-20 cm depth. Using a worst case scenario (.9 g/cm³), to get cosmic ray shielding (400 g/cm²) we can calculate the required depth of regolith using the following formula.

$$\text{density (g/cm}^3\text{)} \times \text{depth (cm)} = 400 \text{ g/cm}^2$$

The resulting depth comes out to be 4.44 meters. Using the same density and calculating for solar flare events (700 g/cm²), the depth of regolith required is now 7.77 meters.

It has since come to our attention that the regolith requirements are considerably less according to a NASA report by John E. Nealy et al. (1989). In their concluding remarks, it is determined that .5 meters of regolith may provide adequate protection for GCR's, yet larger amounts of regolith may be more desirable.

Since this information was obtained after the design of the base was established, it was decided for the purpose of this study, to keep the regolith shield for the Lunar Base at 4.5 meters assuming that a relative density of 1.55 g/cm³ can be obtained through packing of the regolith. We have, however, acknowledged the fact that GCR protection may be achieved with .5 meters.

13.2 Protection Techniques

The following is a study of three different methods for achieving radiation protection using the lunar regolith as a mass between the source and the crew.

Regolith Support Structure

A structural system is employed to suspend the regolith above the module. This provides a sheltered external storage area, allows for easy growth of the base, and the hull is easy to access in case of emergency. However there is an incredible increase in mass through LEO for the structure, unless it can be made from in situ materials. It is very EVA intensive to deploy whether it be done in LEO or on the lunar surface, and it may also require additional systems such as screening or matting to prevent the regolith from falling through the structure.

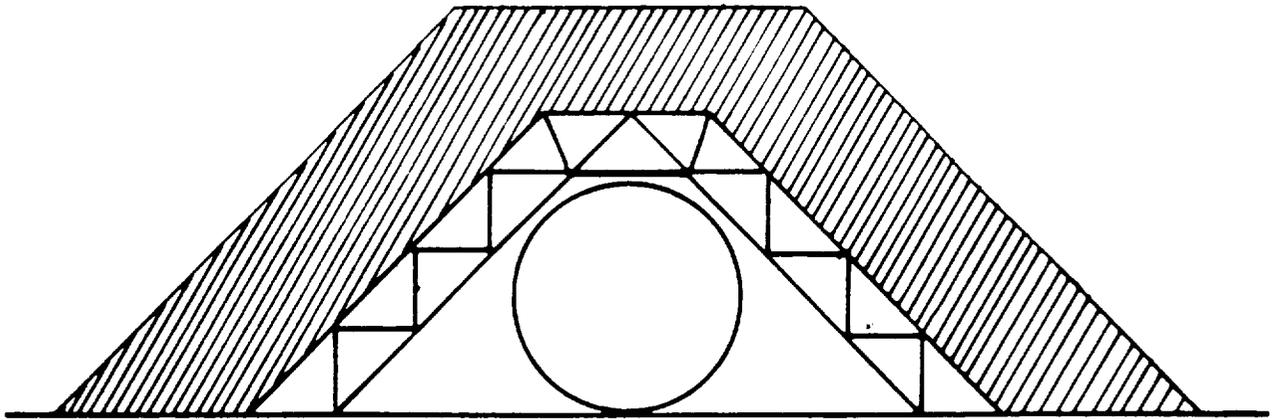


Figure 13.2.1 Regolith support structure

Pros

- Constant temperature storage
- Allows for easy growth
- Easy access to hull

Cons

- Increased mass through LEO
- Time consuming to deploy
- Requires additional systems

No Regolith Support

This is possibly the easiest way to achieve radiation protection using regolith. There is no additional mass through LEO, there are no additional systems needed, and the regolith is merely dumped on top of the module until the desired level is achieved. This does however make it difficult for expansion and hull access due to tons of regolith being between the hull and crew. This method also requires more space between modules due to the 30° slump angle of the regolith.

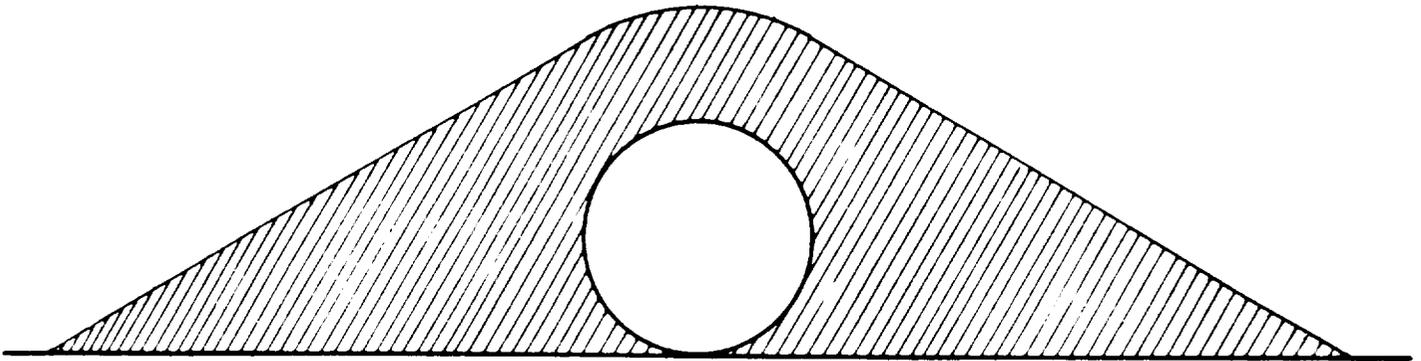


Figure 13.2.2 No regolith support

Pros

- No additional mass for structure
- No additional systems required
- Relatively easy to achieve end result

Cons

- Expansion is difficult
- Requires more space
- Emergency access is difficult

Contained Regolith

Contained regolith to seemed meet many of our requirements and needs, it allowed for easy growth, the system is relatively easy to deploy, the system can lend itself to other uses, and the regolith is contained in a defined area. There is, however, an additional amount of mass through LEO, but it is considerably less compared to that required for the regolith support structure.

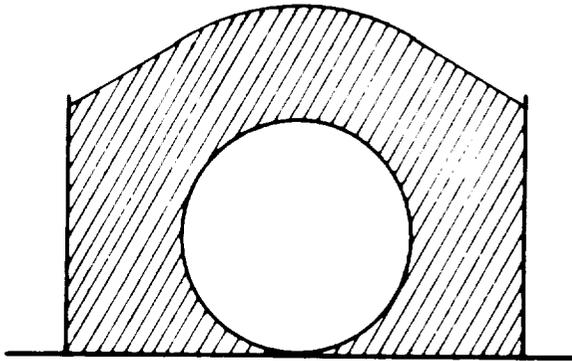


Figure 13.2.3 Contained regolith

Pros

- Allows for easy growth
- Regolith is contained in a defined area
- Relatively easy to deploy
- System can lend itself to other uses

Cons

- Additional mass through LEO

Contained regolith was chosen as the method for radiation shielding for the Lunar Base. It was chosen based on the flexibility of the system, ease of deployment as well as the ease of achieving the end result.

Contained regolith can be achieved through a number of different methods, but the principle remains the same. There is a structure, which acts as a form or a mold, to contain the regolith in a defined area so there is no excess or overspill which may be a hindrance to circulation around the exterior of the modules. The structure can be arranged on a grid system so that the module coverage and unearthing can be a controlled activity. To gain access to the hull, one wall could be removed and the regolith would spill away. This ensures ease of access to the hull for both expansion of the base and also access in case emergency repair is needed (see figure 13.2.4).

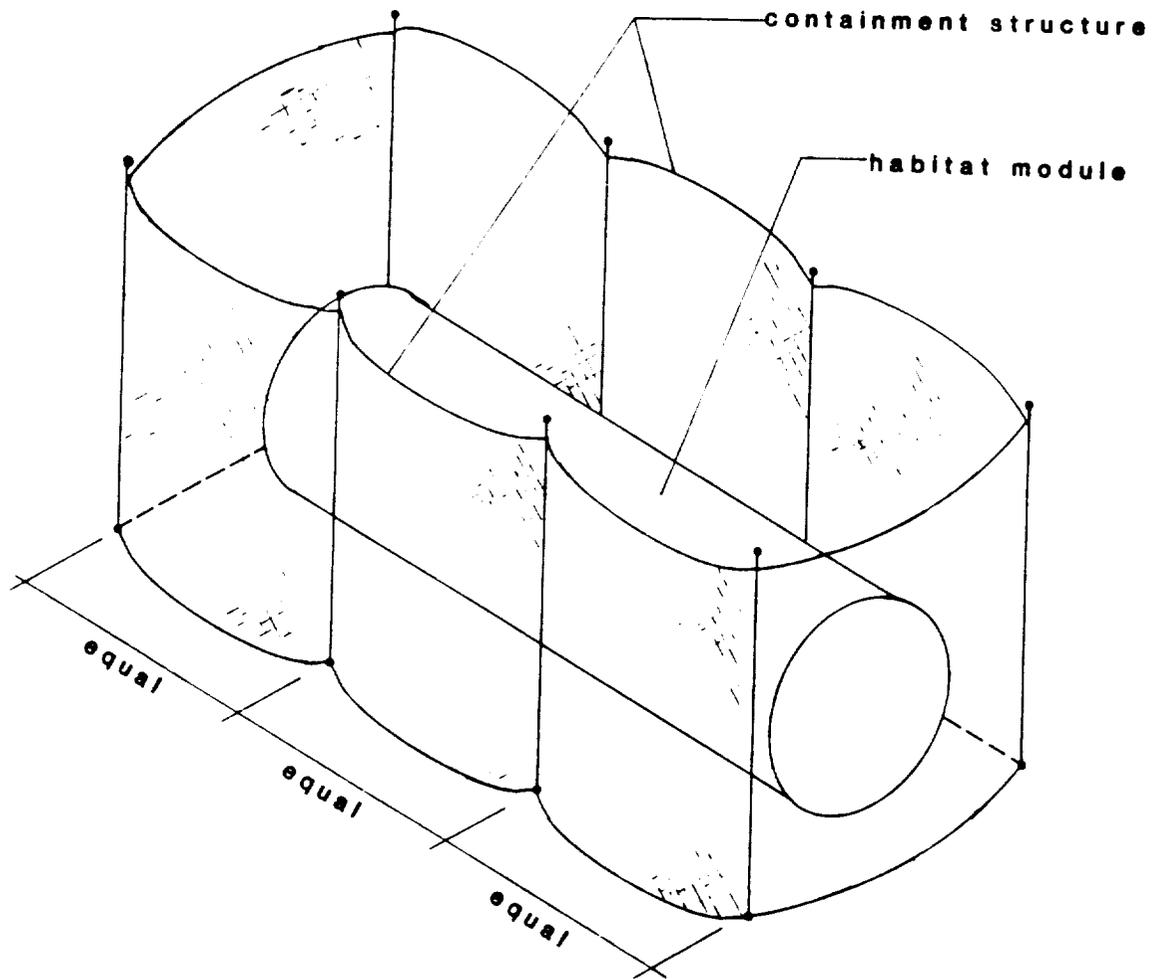


Figure 13.2.4 Regolith containment system

The method for achieving contained coverage chosen by the design team uses a tensile structure. The whole system is a tensile structure loaded internally with regolith. The lateral forces exerted on the structure, which put it into tension, are a result of the weight of the regolith trying to force itself out horizontally against the structure as it is poured into the structure from the top (see figured 13.2.5). The system consists of a composite graphite and high tensile aluminum alloy tube section members on a 4.5 meter grid spacing.

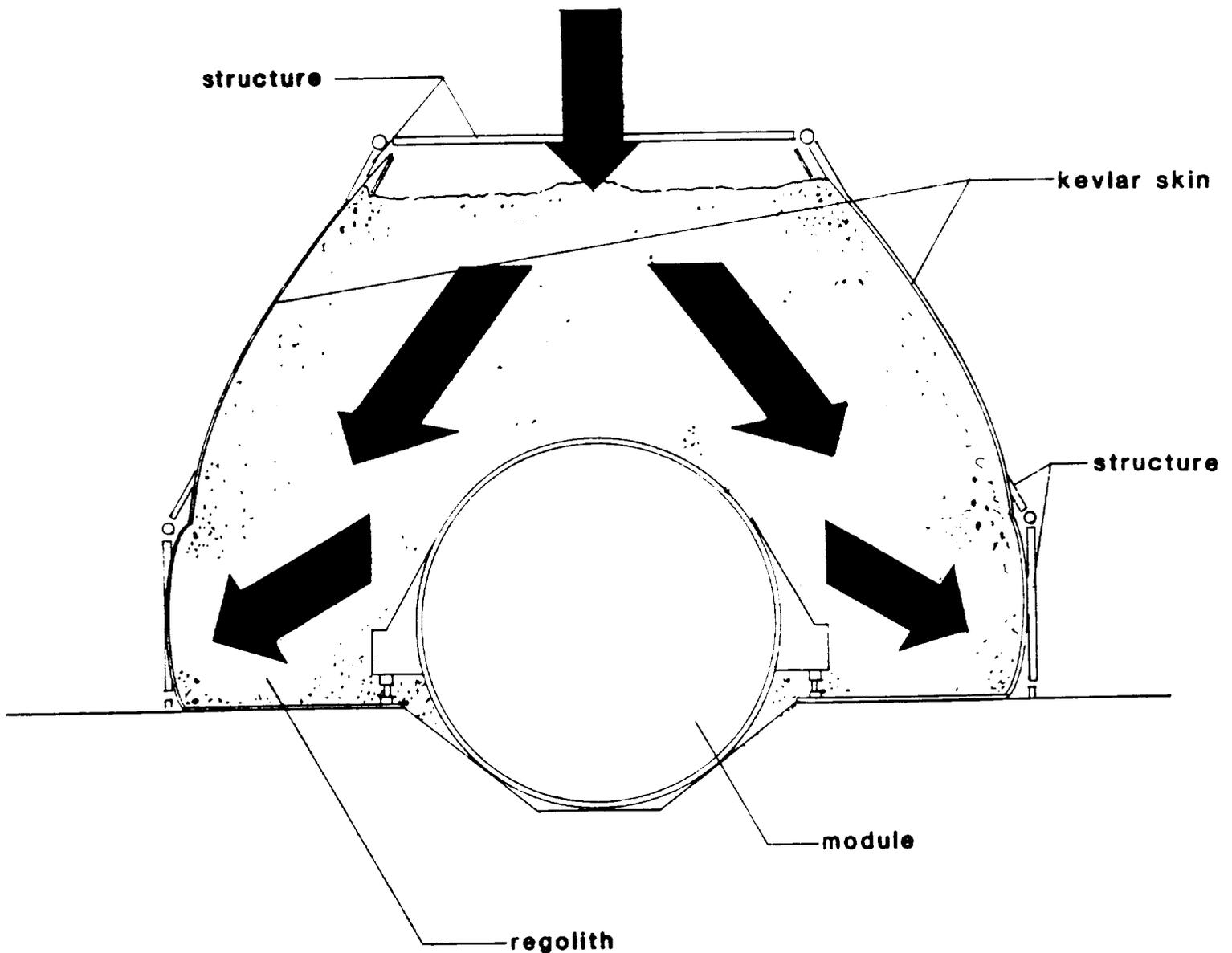
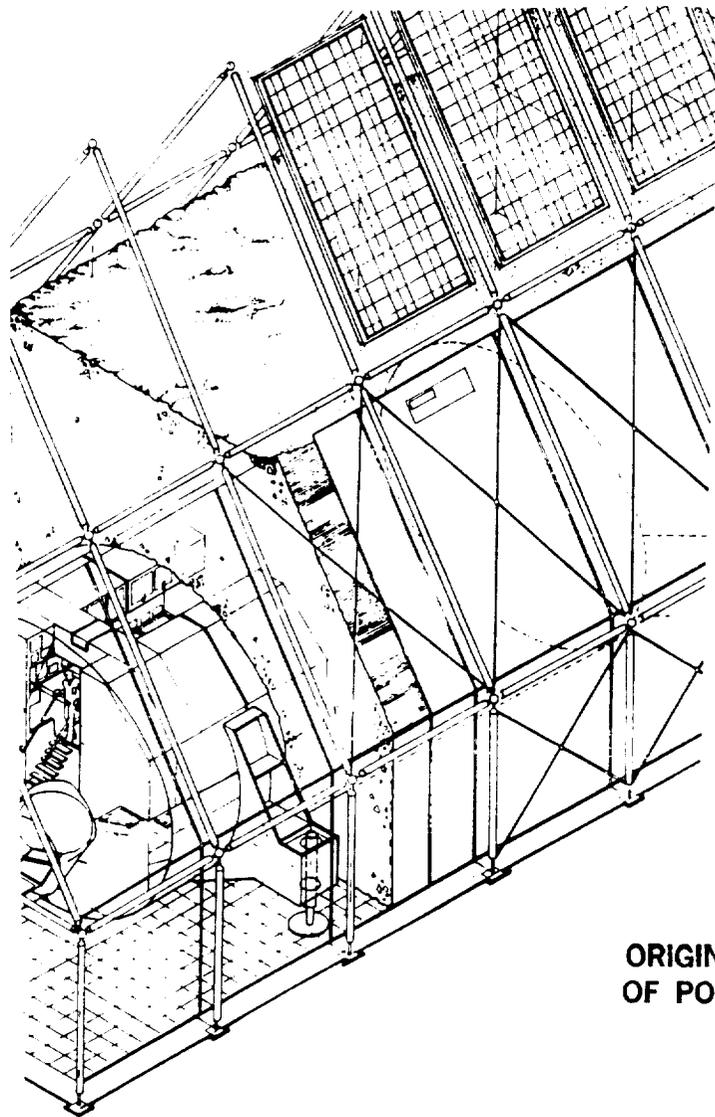


Figure 13.2.5 Loading diagram for regolith containment

The frame has multi-layered Kevlar suspended in the areas which are to receive the regolith. This Kevlar is held off the structure by the use of a track system which is also used in the deployment sequence of the Kevlar. In the areas which do not receive regolith, a substitute material is used, thin multi-layered mylar with a highly reflective surface on the outer side to reflect the intense solar bombardment and act as a thermal barrier. Figure 13.2.6 shows the deployment of the Kevlar and mylar in the system. The system was designed to fold and unfold to make the deployment sequence as easy as possible and thus decreasing the amount of EVA time necessary.



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Figure 13.2.6 Detail of containment system

13.3 Phased Coverage

It was important to design the radiation protection in such a way that it would be coordinated with the phased growth of the base (see figures 12.2.1 a-e). It was felt necessary to cover the base as it grows so that the crew living in the base during the construction phase will have the same protection as when the base is in full operation.

The regolith containment structure is set up on a grid of 4.5 meters as indicated in figure 13.2.4. Each of the modules which receive 4.5 meters of regolith are covered with the structure as they are put in place, and the ends are covered with the Kevlar (see figure 13.3.1). When another module is ready to be placed and covered, the receiving end of the previous module is cleared of regolith by removing the Kevlar at that end.

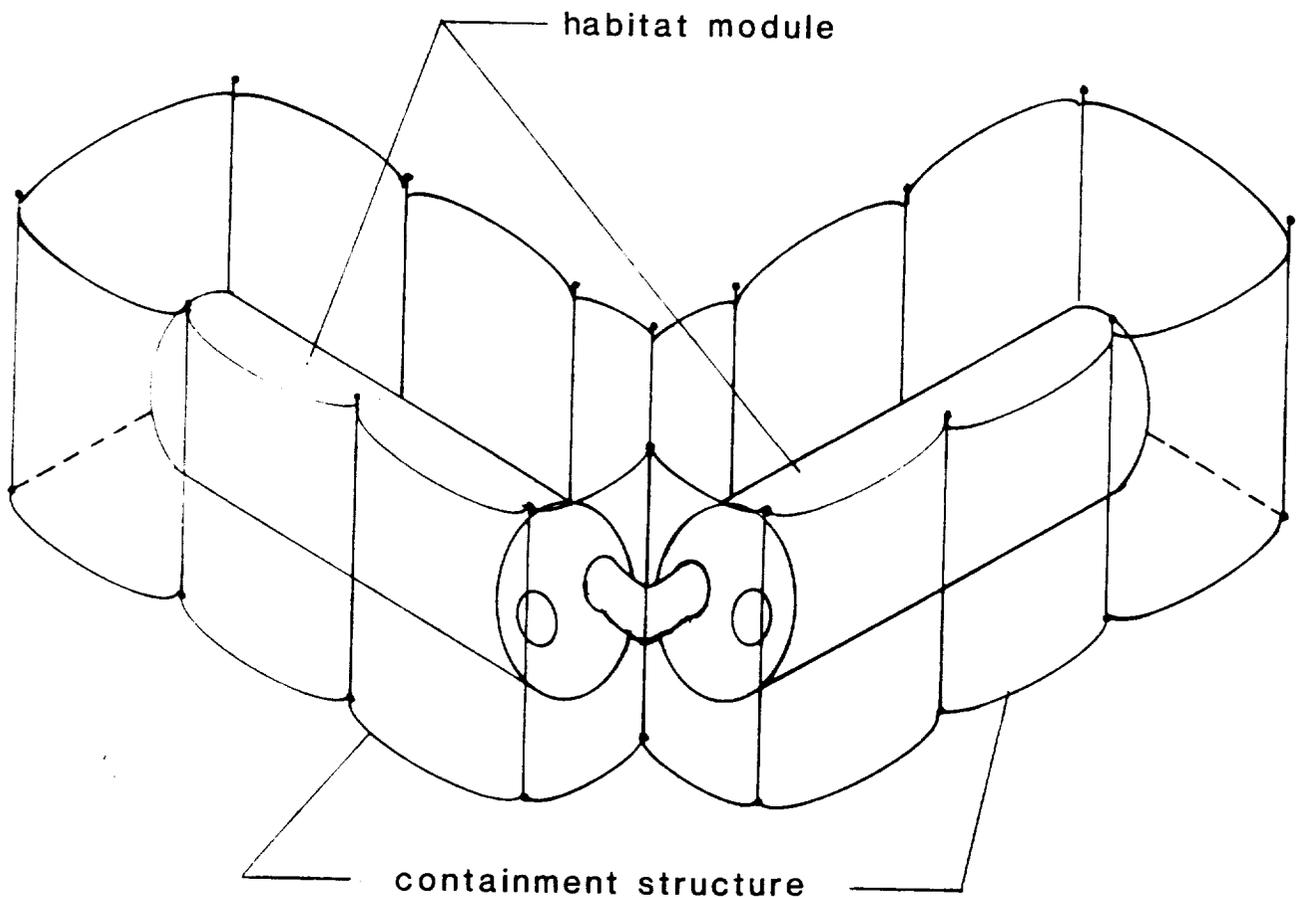


Figure 13.3.1 Base expansion

Construction continues in this manner until the entire base is completed. The completed base can be seen in figures 13.3.2-13.3.5. By having the coverage controlled to such a degree, this also allows for controlled removal of the Kevlar and regolith in case the hull of a module must be accessed for repairs or, in case a module must be replaced entirely.

The structure itself is composed of a limited number of different sized members to make it as simple as possible. By keeping the containment structure simple, and using only a limited number of components, the cost of making specialty members is non-existent.

All module and airlock ports will have flexible connectors attached which will then protrude through the Kevlar to provide an alternate means of access and egress in case of either emergency or as preparation for future expansion.

There are a total of four airlocks to be used in the Lunar Base. Two of the airlocks will be buried in the regolith and will be fixed pieces unless they are taken out for repairs. These airlocks will be dedicated primarily for docking with a pressurized vehicle, but can also be used for pedestrian access egress. The other two airlocks can also be used for docking with a pressurized vehicle, yet their primary purpose is to provide a safe are of egress in the event of an emergency. These two modules can also be moved to different locations on the base if one of the modules is damaged, or after use of the base it is found that the airlock would work more efficiently if it were in a different location.

The airlocks which are not covered will have a large role during the construction phase of the base. These two airlocks will be the main source of access egress for the base during the construction phase, and they will be moved to different locations as the base grows and changes its shape.

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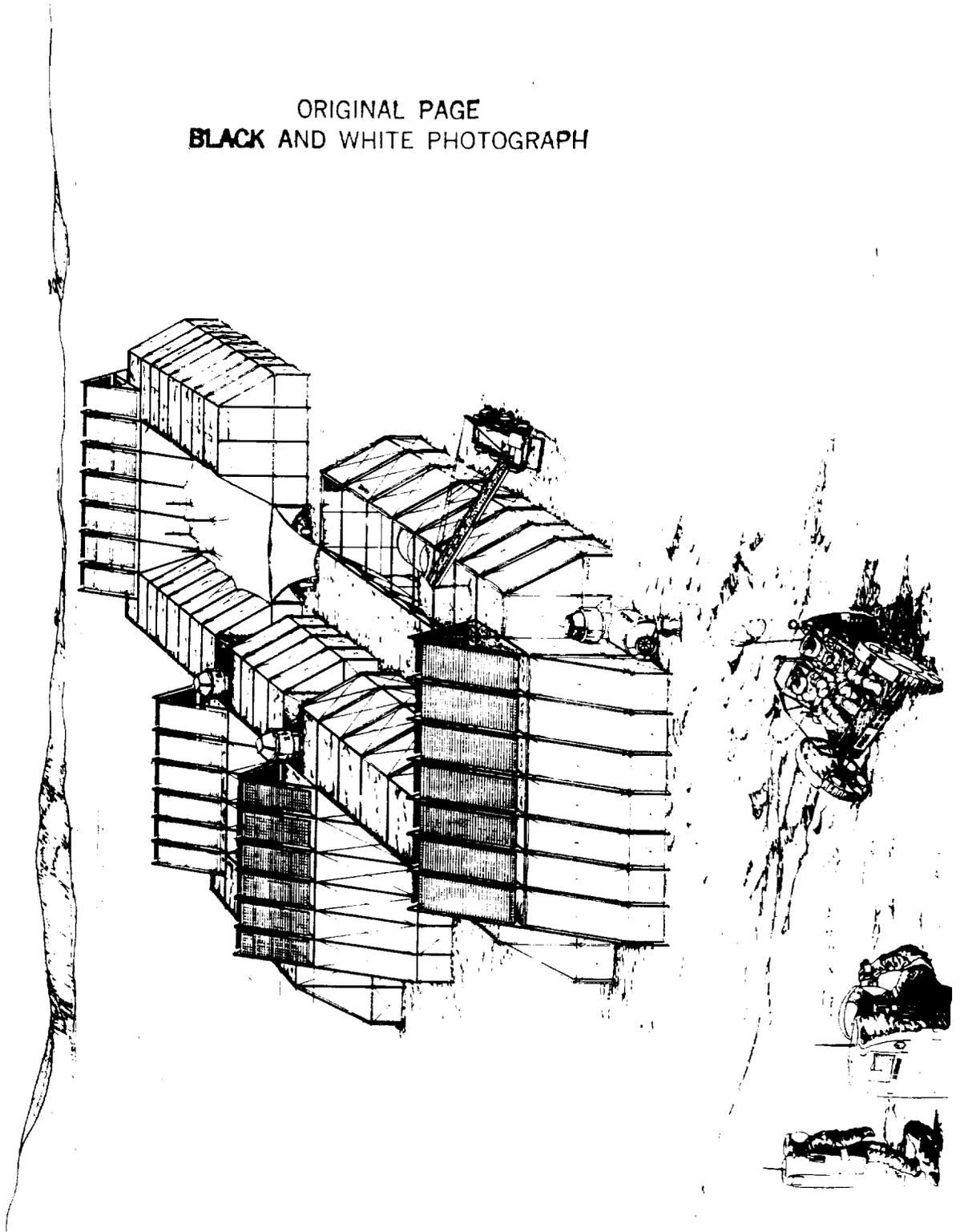


Figure 13.3.2 Lunar base isometric

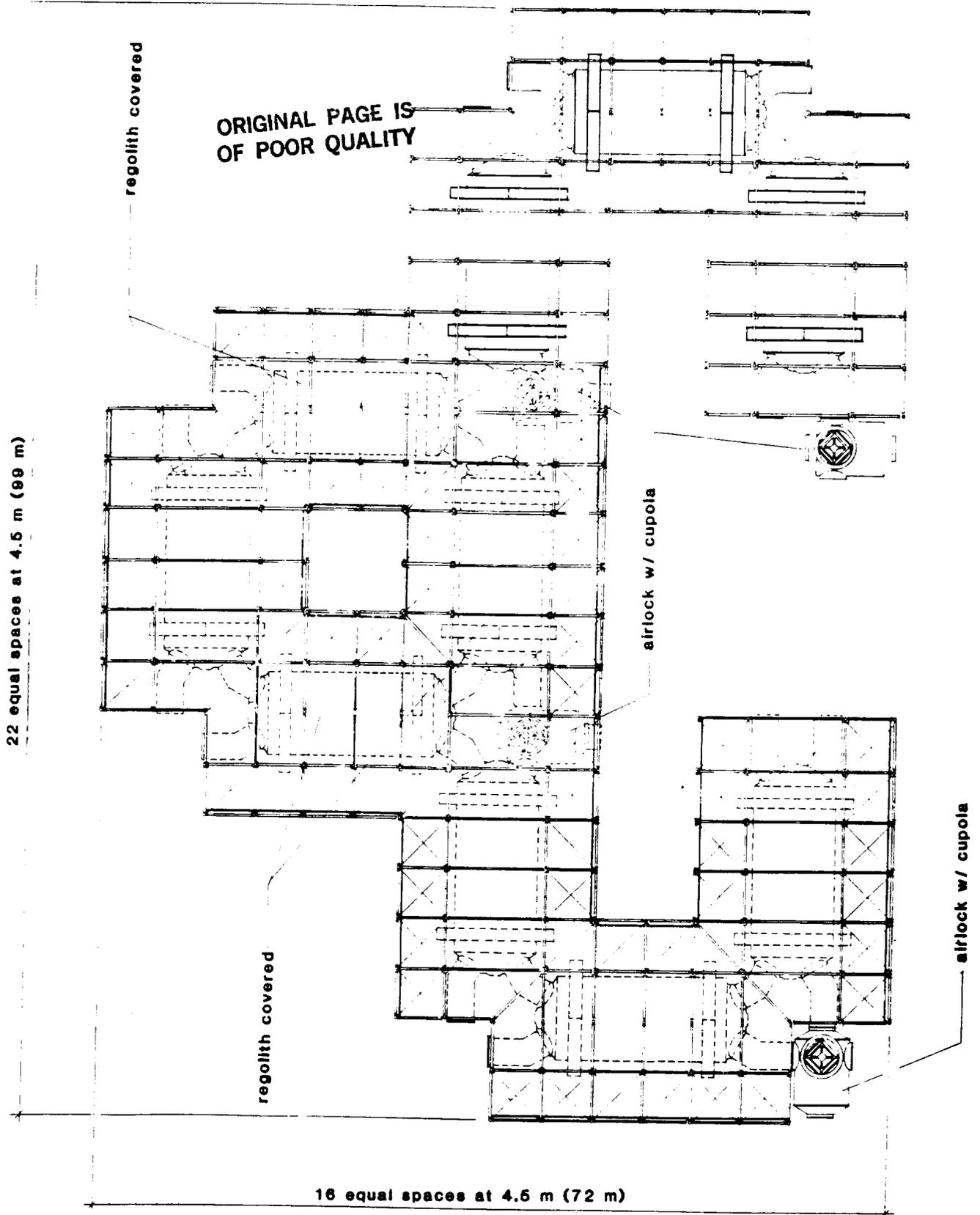


Figure 13.3.3 Lunar base plan

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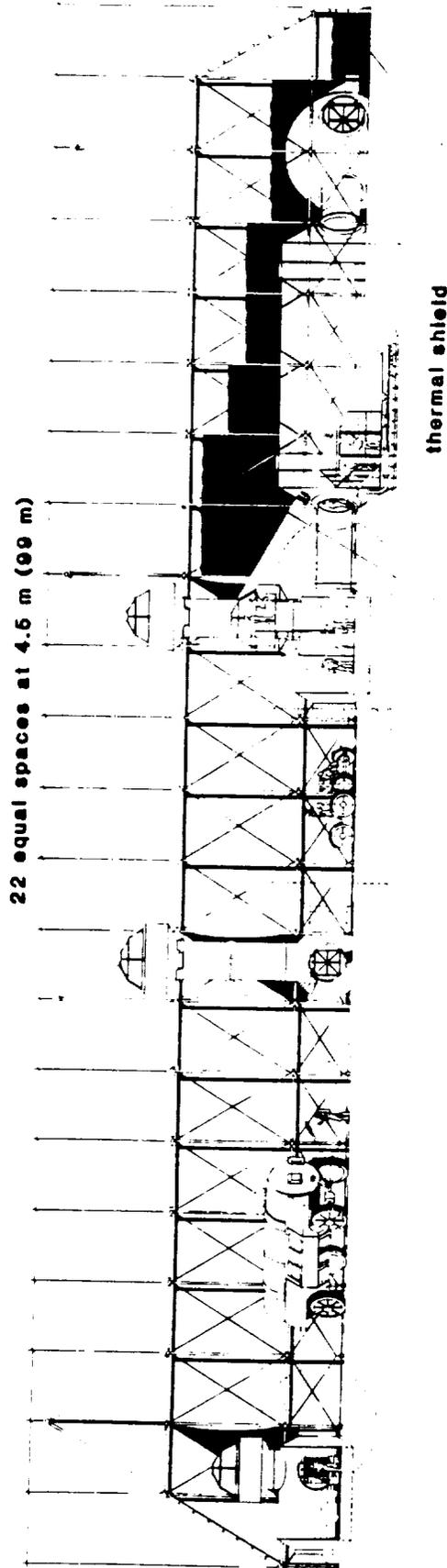


Figure 13.3.4 Lunar base elevation/section

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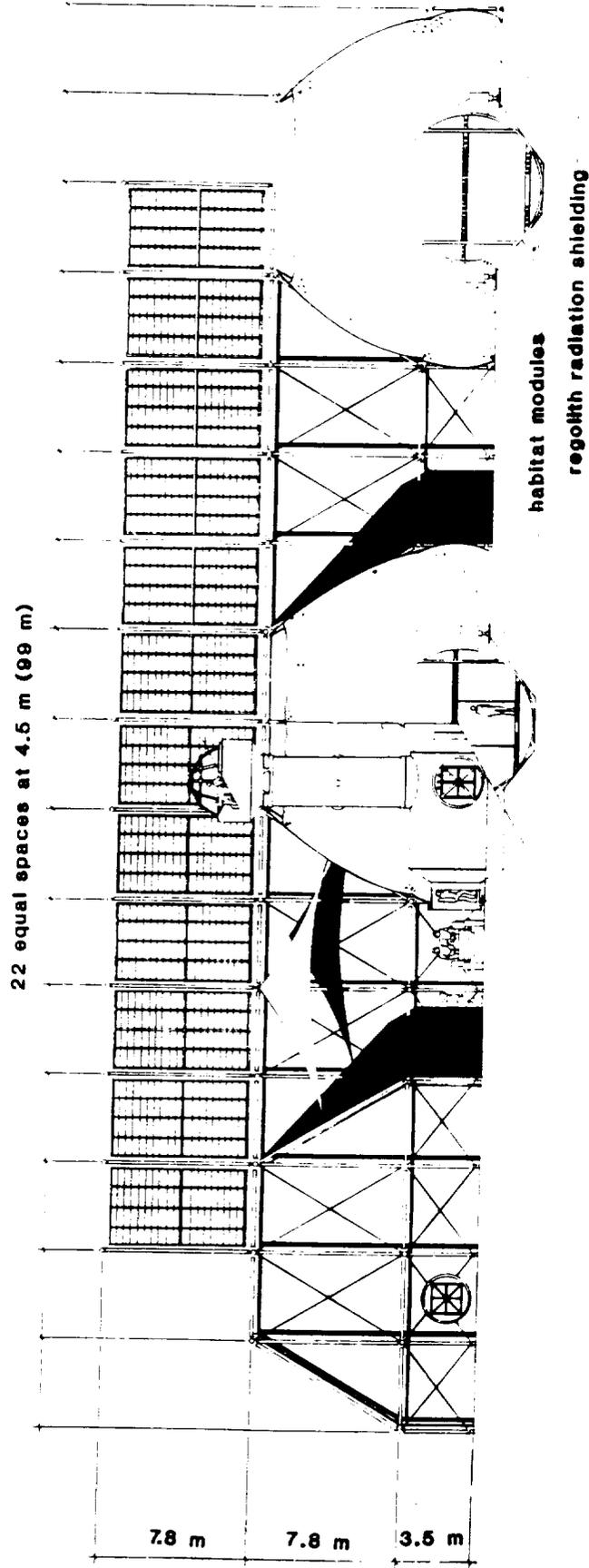


Figure 13.3.5 Lunar base section

14.0 Facility Planning

14.0 Introduction

To perform a complete analysis of the lunar base, all facilities needed to be shown in context with the habitat facility. Before any planning could be done for the lunar base, it was necessary to determine the purpose and functions to be served. The design team felt that the base should be the beginning of man's colonization away from planet Earth, a station for scientific study, and be a testing ground for advanced technologies. The main industrial products of the facility will be LLOX (Lunar Liquid OXYgen) for fuel and human consumption, and the production of construction materials.

It was important to determine the needs of each facility in the way of machinery and equipment as well as storage and physical space requirements. To begin, a complete inventory of all related amenities to each facility was conducted.

As a result, it was found that all of the required facilities could be grouped into four categories, industrial, transportation, living, and science and utility (see figure 14.0.1). Within each of these categories, the functional breakdown is as follows: Industrial-- mining, power plants, manufacturing and processing; Transportation-- landing, launching, vehicle storage and maintenance; Living-- habitat and agricultural facilities; Science and Utility-- solar arrays and observatory sciences.

The site selection was an important issue because the site needed to be as versatile as possible. Access to and from the site needs to be as easy as possible, therefore a site within a few degrees plus or minus latitude of the equator would be ideal.

The base should be located on the near side (the side facing the Earth) of the Moon to minimize communications problems as well as provide a psychological link with Earth.

The site should offer a rich mineralogical and geological composition, providing access to mare and highland regions. The mare is a good location for the facility because it provides flat areas for construction areas, living areas, materials processing plants, solar arrays and telescope fields, and landing facilities. The highlands are good for mining, geological study, and natural shielding from incoming low angle projectiles (natural and man made). Therefore, a site on the mare with near access to the highlands would be ideal.

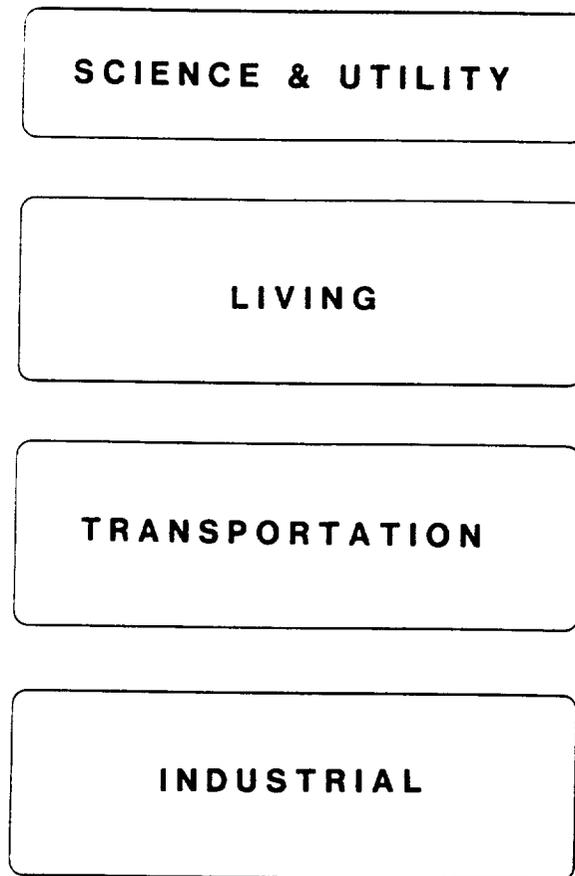


Figure 14.0.1 Zoning diagram for lunar base

14.1 Facility Design

The site chosen for the base was in the vicinity of the Apollo 14 landing site. This was decided because the Apollo 14 site seemed to offer everything we were looking for in the way of site diversity. It is on the near side, has access to both mare and highland regions, and is only a few degrees south of the equator.

The design of the base is linear with the long axis being north-south. The linear configuration was derived by separating conflicting facilities as much as possible and at the same time organizing the zones to function efficiently (see figure 14.1.1).

The north side of the facility is where the solar array fields, astronomical telescopes, and the communication discs are located. These facilities are isolated from the base at a comfortable distance of 10 Km to provide as dust free of an environment as possible. Also, these facilities will require a very minimal amount of maintenance and attention and will be monitored only periodically.

The next zone south is the living zone. This is where the habitat and agriculture facilities will be housed. Heat radiators and storage for water and other usable supplies are also located in the living zone. The living zone is isolated from the other zones for various reasons. There will be construction and much vehicle traffic around the living area due to crew members traveling between the southern zones and the living zone. This will create a dust problem as mentioned above which needs to be compensated for by distance. The habitat facilities are kept at a safe distance from the landing and industrial zones in case of an accident with an incoming or out going space craft, or an explosion at either of the two facilities.

Landing and launching facilities are the next zone as we travel south through the site. This zone is kept between the industrial and living zones to allow easy access by both, and is the point of access of the base for outsiders. The landing zone is equipped with three landing pads, a hanger facility and an elevated transportation system. The landing pads are separated diagonally to minimize the distance between each in

the north-south plane. By having the pads staggered diagonally, they all have clear access from the east, which is the orbital path for incoming vehicles, while not being too far separated in the north south plane. The elevated transportation system is provided for the transportation of materials and supplies to and from the landing zone, to both the industrial and living zones without dedicating crew personnel for the task. The hanger facility is provided for repair, maintenance, and storage of space crafts, vehicles and other pieces of machinery.

At the south end of the base is the industrial zone, containing the LOX liquefaction plants, cast and sintered basalt facilities, a linear accelerator, and the power plant for the base. Here, processing of all materials is performed. LOX and construction materials are produced from raw regolith and then transported to the appropriate locations throughout the facility either by vehicle or by elevated transport. The liquid oxygen will be sent off in pressurized containers to rendezvous with space crafts waiting to be refueled or to a space port which acts as a fueling station for other vehicles. Some of the oxygen will also be used on site for life support systems as well. The oxygen sent off as fuel will be done so with the use of the linear accelerator. The power plant is located in the industrial zone for two reasons, this is where the power demands will be highest, and also it was felt that the further we kept the nuclear reactors from the living and agricultural facility, then the risk of danger would be lower.

The over all facility design illustrated in figure 14.1.1 is felt by the design team to be an effective solution to the design issues faced when designing a facility such as the Lunar Base.

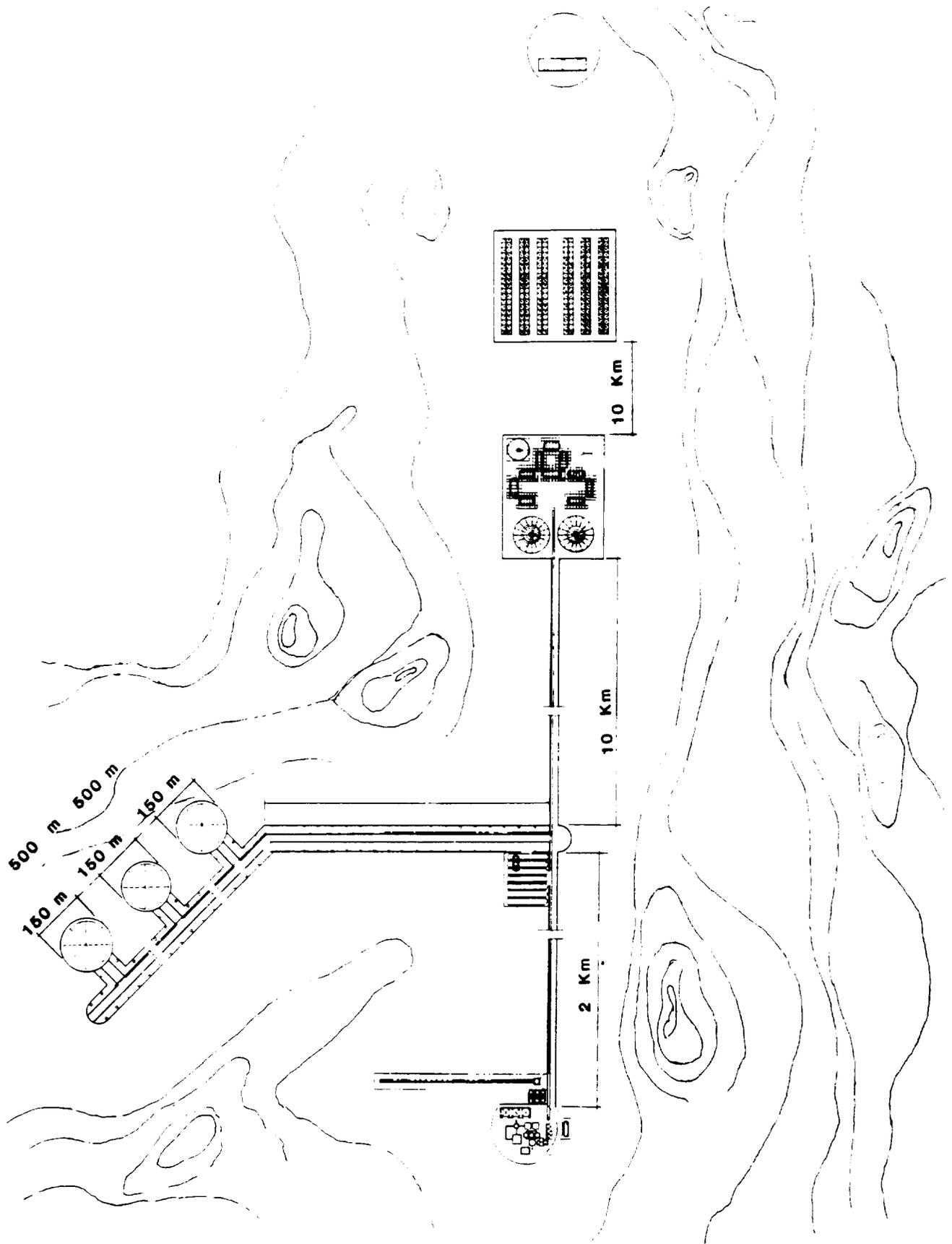


Figure 14.1.1 Site plan for lunar base facility

**PART IV
CONCLUSIONS**

15.0 Lessons Learned

15.1 Overview

The goal of this study was to formulate facts on human reactions to partial gravity environments, derive design requirements based on these facts and apply the requirements to a partial gravity situation. The approach was to compare partial gravity with Earth gravity (1g) and microgravity to derive design differences.

Partial gravity is similar to Earth gravity (1g) except for human locomotion; however, differs greatly from microgravity in that astronauts cannot sleep on the walls and ceilings and are restricted to a 7' (2.13 m) usable height. Locomotion differences in partial gravity cause the human body to have a much greater forward body inclination as well as "bouncing" higher than in Earth gravity (1g). Walking and running speeds are slower in partial gravity and it is harder to stop due to reduced friction.

It was also determined that a "two-level" interior configuration is the most efficient use of volume as well as minimizing the weight/volume ratio. Separation of working and living areas as well as public and private areas is the most efficient functional arrangement.

From the viewpoint of a lunar base, it was concluded that radiation protection is desirable at least for part of the base to protect humans from solar flares. Lunar regolith coverage of the modules was determined to be the best method of radiation protection. Lunar regolith can also be a very good source of LOX (liquid oxygen) and material for use in construction (cast and sintered basalt). Regolith construction can produce materials such as structures (cast basalt), paved surfaces (sintered basalt) and cables (spun basalt).

16.0 Outstanding Technology

16.1 Overview

Research into the long term effects of partial gravity on the human body is much needed to determine how the environment changes humans, which in turn will effect design.

A Heavy Lift Launch Vehicle (HLLV) must be developed to carry the modules into LEO, where a Space Operations Center (SOC) must be in place. The HLLV must be able to carry a module 22' (6.7 m) by 57.5' (17.2 m) that weighs 77,000 lbs. (35,000 kg). From the SOC, there needs to be an Orbital Transfer Vehicle (OTV) that can carry the module to an orbit around the Moon. A lander that can deliver the module to the surface of the Moon must also be developed. Once the module is on the surface there must be a vehicle that can carry the module to its final destination. This fleet of vehicles are essential to bring this concept to reality.

We are assuming that the mining equipment can also be used to cover the modules with regolith for radiation protection. However, this seems to be a laborious process that might require additional equipment.

Appendix A

The following is a condensed version of the scenario developed and used in the planning of the lunar base proposal.

Between January 1998 and August 2003, there are a scheduled 18 unmanned lunar missions. The intent of these missions being; to conduct a number of orbital scientific experiments, several lander and sample return missions, and to place equipment on the surface for later use

We have not continued the scenario past 12/2008 because, at this point, the scenario begins to grow at a tremendous rate due to the use of lunar materials. The lunar materials are used for production of LOX, construction materials, plant growth etc.. By using lunar derived LOX, there is no longer a need to bring O₂ from the Earth for use on the lunar surface or for fueling other crafts for use in the Earth Moon system, or the Earth Mars system. The use of lunar materials for construction falls mainly into the use of basalts. Through the processes of casting, sintering or even microwaving, basalt becomes a very usable and strong material. These materials in turn are used in the fabrication of habitable or storage structures, tools and paved surfaces respectively. By using Lunar derived foods, the demand for Earth launched foods would be reduced, and the base would be further on its way to becoming more self sufficient.

From here on, the scenario will be broken down into tabular form by month and year, identifying activities to be carried out and supplies landed on the lunar surface.

PARTIAL GRAVITY HABITAT STUDY

<u>Month</u>	<u>Year</u>	<u>Contents</u>	<u>Mass</u>
2,	2004	Power unit 1.5 Mw	11.4 MT
		ECLSS	4.8 MT
		Crane	1.9 MT
		H ₂ liquefaction plant	1.8 MT
		Geology experiment	0.1 MT
4,	2004	Habitat module	11.7 MT
		Regolith structure members	0.3 MT
		Advanced ECLSS lab.	5.8 MT
		Contingency	1.3 MT
		Digger	0.9 MT
6,	2004	Airlock node	9.8 MT
		Fluorine for LOX plant	9.0 MT
		Cable	1.0 MT
		Portable Geophysics equipment	0.1 MT
		Geophysics station	0.1 MT
7,	2004	Unmanned sample collection	
8,	2004	4 men, 6 months food	7.2 MT
		Conveyors	1.2 MT
		Regolith sorter	2.4 MT
		LOX liquefaction plant	1.8 MT
		Sample analysis equipment	0.2 MT
		Unpressurized 10 Km manned rover	0.2 MT
1,	2005	Unmanned sample collection	
2,	2005	Lunar lander facility	8.0 MT
		4 men, 6 months food (crew change)	5.0 MT
4,	2005	Propellant refill vehicles	14.0 MT
		Preliminary sample laboratory	2.2 MT
		Biomedical laboratory	3.7 MT
		Geophysical station	0.1 MT
6,	2005	Habitat module	11.7 MT
		Manned exploration vehicle	6.0 MT
		H ₂ for manned vehicle	2.3 MT

7, 2005	Unmanned sample mission Manned exploration mission	
8, 2005	4 men, 6 months food (crew change)	2.9 MT
	Initial monitoring telescope	0.1 MT
	9 monitoring telescopes	0.1 MT
	Optical telescope	0.9 MT
	Radio interferometer telescope	2.1 MT
	Solar observatory	2.3 MT
	Earth observatory	2.1 MT
	Regolith structure members	2.3 MT
	Contingency	0.2 MT
10, 2005	Habitat module	11.7 MT
	Regolith structure members	6.8 MT
	Cable cart	0.8 MT
	Contingency	0.7 MT
11, 2005	Airlock node	9.8 MT
	#2 fluorine shipment	9.0 MT
	LOX plant added to facility	
	Science re-supply	1.1 MT
	Geophysical station	0.1 MT
12, 2005	#2 power unit 1.5 Mw	11.4 MT
	Thermal control for habitat	6.1 MT
	Part of ECLSS for habitat	2.5 MT
1, 2006	Unmanned sample collection	
2, 2006	4 men, 6 months food (crew change)	2.9 MT
	Cable	1.0 MT
	Part of ECLSS	9.1 MT
4, 2006	Last of ECLSS	13.4 MT
	Extreme UV telescope	0.8 MT
	X-ray telescope	0.1 MT
	Geology experiment equipment	2.9 MT
	Portable geophysics equipment	0.1 MT
	H ₂ fuel for manned vehicle	2.6 MT
5, 2006	Manned exploration (2.6 MT fuel)	18.2 MT

PARTIAL GRAVITY HABITAT STUDY

5, 2006	Regolith structure members	8.6 MT
	Regolith structure members	8.6 MT
	#2 LOX liquefaction plant	1.8 MT
	Resource facility re-supply	1.0 MT
6, 2006	#3 liquefaction plant	1.8 MT
	#3 fluorine shipment	9.0 MT
	Exchange plant added to LOX facility	
	#3 power unit 1.5 Mw	11.4 MT
7, 2006	Unmanned sample collection	
8, 2006	8 men, 6 months food etc.	5.8 MT
	Sample analysis equipment	0.2 MT
	Unpressurized 10 Km manned rover	0.2 MT
	2 geophysical stations	0.2 MT
	Portable geophysical stations	1.2 MT
	Microprobe laboratory	3.2 MT
9, 2006	Habitat module	11.7 MT
	Regolith structure members	6.8 MT
	H ₂ fuel for vehicle	1.5 MT
	Manned exploration (1.5 MT fuel)	10.5 MT
10, 2006	Thermal control for habitat module	6.1 MT
1, 2007	Unmanned sample collection 100 Km local traverse mission	
2, 2007	6 months food etc. 8 crew (change)	5.1 MT
	ECLSS for habitat	5.9 MT
	H ₂ fuel for manned vehicle	2.0 MT
4, 2007	Airlock node	9.8 MT
	Heat radiators	3.3 MT
	Part #4 fluorine supply	2.3 MT
	#4, #5 LOX liquefaction plants added	3.6 MT
	Geophysical station	0.1 MT
	H ₂ fuel for manned vehicle	0.9 MT
5, 2007	Manned exploration (2.9 MT H ₂)	19.8 MT

PARTIAL GRAVITY HABITAT STUDY

6,	2007	Dry LTL landed to be refueled	14.6 MT
7,	2007	Unmanned sample collection	
8,	2007	6 months food etc. 8 crew (change)	5.1 MT
		Last of #4 fluorine supply	6.7 MT
		Exchange LOX plant added	
		Part of #5 fluorine supply	0.4 MT
		Exchange LOX plant added	
		2 geophysical stations	0.2 MT
		H ₂ fuel for manned vehicle	0.6 MT
9,	2007	Manned exploration (0.6 MT H ₂)	4.2 MT
		#4 power plant 1.5 Mw	11.4 MT
		Last of #5 fluorine supply	8.6 MT
		Exchange LOX plant added	
10,	2007	#5 power plant 1.5 Mw	11.4 MT
		Part #6 fluorine supply	8.6 MT
		Exchange LOX plant added	
12,	2007	Last of #6 fluorine supply	0.4 MT
		Exchange LOX plant added	
		#6 power plant 1.5 Mw	11.4 MT
		#6 LOX liquefaction plant	1.8 MT
		Part of #7 fluorine supply	6.4 MT
		Exchange LOX plant added	
1,	2008	Unmanned sample collection 100 Km local traverse	
2,	2008	6 months food, 12 crew (add 4 crew)	7.9 MT
		Last of #7 fluorine supply	2.6 MT
		#7 LOX liquefaction plant	1.8 MT
		Resource facility re-supply	0.7 MT
4,	2008	#7 power unit 1.5 Mw	11.4 MT
		#8 LOX liquefaction plant	1.8 MT
		Part of #8 fluorine supply	3.9 MT
		Cable	1.0 MT
		Geophysical station	0.1 MT
		H ₂ fuel for manned vehicle	1.8 MT

5, 2008	Manned exploration (1.8 MT H ₂)	12.6 MT
	Cable	1.0 MT
	Resource facility re-supply	1.0 MT
	Life science re-supply	0.3 MT
	Last of #8 fluorine supply	5.1 MT
	#9 fluorine supply	9.0 MT
	LTL remains to refuel next trip	14.6 MT
8, 2008	6 months food, 12 crew (4 change)	7.9 MT
	Part of #10 fluorine supply	2.6 MT
	2 geophysical stations	0.2 MT
	H ₂ fuel for manned vehicle	2.3 MT
9, 2008	Manned mission (2.3 MT H ₂)	15.7 MT
	#8 power plant 1.5 Mw	11.4 MT
	Astronomy re-supply	0.4 MT
	Last of #10 fluorine supply	6.4 MT
	#10 LOX liquefaction plant	1.8 MT
10, 2008	#11 fluorine supply	9.0 MT
	#11 LOX liquefaction plant	1.8 MT
	Part of #12 fluorine supply	5.3 MT
	Digger	0.9 MT
	Regolith sorter	2.4 MT
	Conveyors	0.6 MT
11, 2008	Last of #12 fluorine supply	3.7 MT
	#9 power plant 1.5 Mw	11.4 MT
	#12 LOX liquefaction plant	1.8 MT
	Part of #13 fluorine supply	3.1 MT
12, 2008	Last of #13 fluorine supply	5.9 MT
	#10 power plant 1.5 Mw	11.4 MT
	#13 LOX liquefaction plant	1.8 MT
	Resource facility re-supply	0.9 MT

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